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Review

Progress in physical oceanography of the Baltic Sea during the 2003–2014 period

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ABSTRACT

We review progress in Baltic Sea physical oceanography (including sea ice and atmosphere–land interactions) and Baltic Sea modelling, focusing on research related to BALTEX Phase II and other relevant work during the 2003–2014 period. The major advances achieved in this period are:

- Meteorological databases are now available to the research community, partly as station data, with a growing number of freely available gridded datasets on decadal and centennial time scales. The free availability of meteorological datasets supports the development of more accurate forcing functions for Baltic Sea models.
- In the last decade, oceanographic data have become much more accessible and new important measurement platforms, such as FerryBoxes and satellites, have provided better temporally and spatially resolved observations.
- Our understanding of how large-scale atmospheric circulation affects the Baltic Sea climate, particularly in winter, has improved. Internal variability is strong illustrating the dominant stochastic behaviour of the atmosphere.
- The heat and water cycles of the Baltic Sea are better understood.
- The importance of surface waves in air–sea interaction is better understood, and Stokes drift and Langmuir circulation have been identified as likely playing an important role in surface water mixing in sea water.
- We better understand sea ice dynamics and thermodynamics in the coastal zone where sea ice interaction between land and sea is crucial.
- The Baltic Sea's various straits and sills are of increasing interest in seeking to understand water exchange and mixing.
- There has been increased research into the Baltic Sea coastal zone, particularly into upwelling, in the past decade.
- Modelling of the Baltic Sea–North Sea system, including the development of coupled land–sea–atmosphere models, has improved.

Despite marked progress in Baltic Sea research over the last decade, several gaps remain in our knowledge and understanding. The current understanding of salinity changes is limited, and future projections of salinity evolution are uncertain. In addition, modelling of the hydrological cycle in atmospheric climate models is severely biased. More detailed investigations of regional precipitation and evaporation patterns (including runoff), atmospheric variability, highly saline water inflows, exchange between sub-basins, circulation, and especially turbulent mixing are still needed. Furthermore, more highly resolved oceanographic models are necessary. In addition, models that incorporate more advanced carbon cycle and ecosystem descriptions and improved description of water–sediment interactions are needed. There

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is also a need for new climate projections and simulations with improved atmospheric and oceanographic coupled model systems.

These and other research challenges are addressed by the recently formed Baltic Earth research programme, the successor of the BALTEX programme, which ended in 2013. Baltic Earth will treat anthropogenic changes and impacts together with their natural drivers. Baltic Earth will serve as a network for earth system sciences in the region, following in the BALTEX tradition but in a wider context.

Contents

Introduction

The Baltic Sea (Fig. 1) is a small intra-continental, shallow coastal sea under severe human-induced pressures, such as global climate change, excess nutrient release, pollution, ammunition dumping, overfishing, and various engineering-based modifications, including the strong growth of coastal settlement, hydro- and nuclear power plants, massive wind farms, gas pipelines, and various bridge and tunnel crossings. At the same time, the Baltic Basin is used for many purposes, such as intensive agriculture, shipping, and recreation. There is a growing need for thorough knowledge of marine ecosystem functioning and how it is changing with time. Knowledge of the physical functioning of the Baltic Sea marine system provides a basis for understanding many features (and their interactions), such as transports, transformation processes, and dilution, for which water, heat, and energy cycles largely determine the boundary conditions. The BALTEX programme (Reckermann et al., 2011; BALTEX articles available at: http://www.baltex-research.eu/publications/library.html), now completing its second phase (2003–2013), has served as a successful scientific network in the Baltic Sea region for the twenty years from 1993 to 2013. Though these years have seen great social and political developments, BALTEX has remained a focal point for regional climate and environmental research. These efforts have

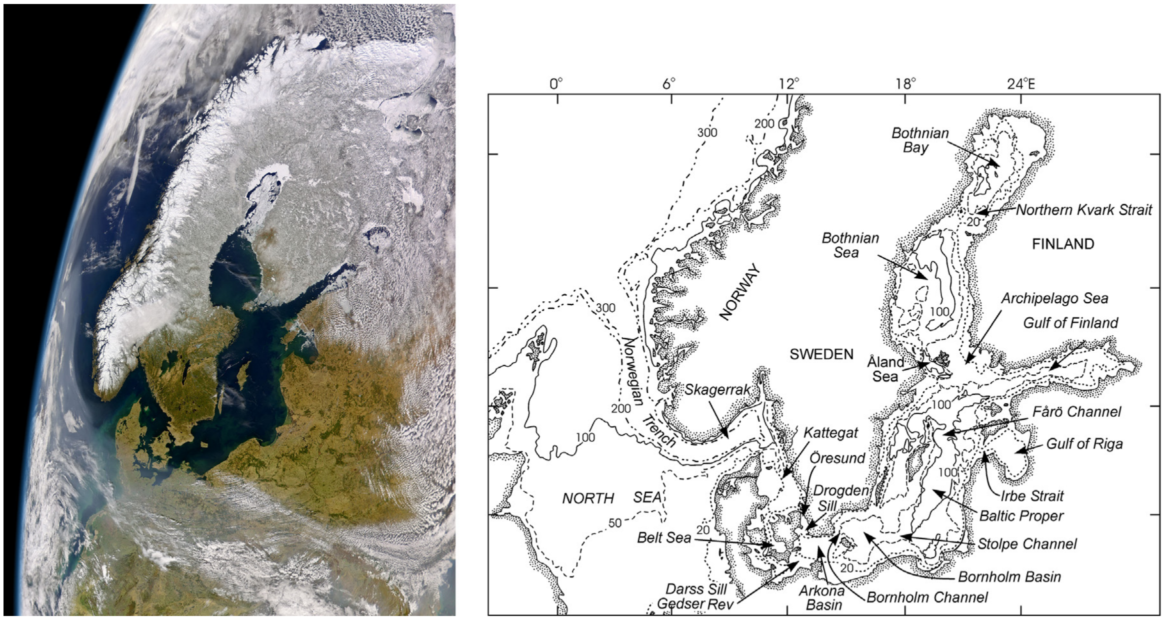

Fig. 1. The Baltic Sea on 1 April 2004 as seen from the SeaWiFS satellite (courtesy of NASA/Goddard Space Flight Center, http://visibleearth.nasa.gov) and the Baltic Sea–North Sea region with depth contours indicated (from Omstedt et al. (2004)).

generated new research and trustworthy networking around the Baltic Sea.

At an early stage, the BALTEX programme focused on collecting data on a great many variables and from the whole drainage basin. Precipitation and river runoff data were prioritized as were data on land and sea temperatures, ice and snow, and salinity. The available data were compiled into databases and used in analyzing the water and heat balances (Omstedt et al., 2004; Raschke et al., 2001). New technological improvements, for example, in precipitation measurement at sea, automatic stations, turbulence measurement, and data quality checks, were important advances. Major radar and satellite developments resulted in new products serving as new scientific tools to help improve our understanding of the Baltic Sea together with its drainage basin's water and heat balances.

Baltic Sea regional modelling has a long tradition and addresses many problems (e.g., Omstedt et al., 2004; Leppäranta and Myrberg, 2009). Operational models have been in use for several decades, teaching scientists to combine theoretical and observational considerations. The development of coupled regional land–sea–atmosphere models has been a major activity in BALTEX, as has improving all model components of the earth system model. The past decade has also seen great improvement in the creation of reanalysis datasets by assimilating data into models that optimally describe nature. This effort has been dominated by work in the meteorological community, and several reanalysis products on decadal time scales are now available and being used in BALTEX research to force hydrological and Baltic Sea models and to provide lateral boundaries in regional climate modelling (e.g., BACC I, 2008; BACC II, in preparation).

BALTEX started by focusing on physical processes in order to address the water and energy cycles of the Baltic region (BALTEX Phase I, 1993–2002). Phase II of BALTEX (2003–2013) also addressed environmental and climate change problems (Fig. 2). The importance of understanding the CO_2–O_2 system in the Baltic Sea made it essential to connect studies of multiple system stressors, such as climate change, eutrophication, and acidification (Edman and Omstedt, 2013). Biogeochemical modelling on land and in the Baltic Sea has made major achievements, demonstrating the strength of the BALTEX approach by coupling land, atmosphere, and sea. These models will play an important role in future research aiming to improve our understanding of the earth system and are further discussed in this review.

This review discusses and summarizes the main lines of development in physical oceanography over the past decade in BALTEX Phase II and related programmes. A similar review of the BALTEX Phase I period was conducted by Omstedt et al. (2004). Other relevant studies of Baltic Sea physics or related matters have been published in recent years. Soomere et al. (2008) reviewed the physical oceanography of the Gulf of Finland. Reissmann et al. (2009) reviewed the various mixing mechanisms in the Baltic Sea, and Meier et al. (2006a,b) studied Baltic Sea deep-water ventilation. Lehmann and Myrberg (2008) reviewed upwelling in the Baltic Sea, while process-based modelling of coastal seas, including the Baltic Sea, was treated in a book by Omstedt (2011). Baltic Sea physics and related processes were examined in books by Feistel et al. (2008) and Leppäranta and Myrberg (2009).

The main aims of the present paper are: (1) to investigate the development of the physical oceanography of the Baltic Sea (including sea ice and interaction with atmosphere and land) and the development of Baltic Sea modelling over the last decade; and (2) to identify the current state of the art of research, highlighting what is already known and what seem to be the key unresolved problems to be addressed in the future. This review is

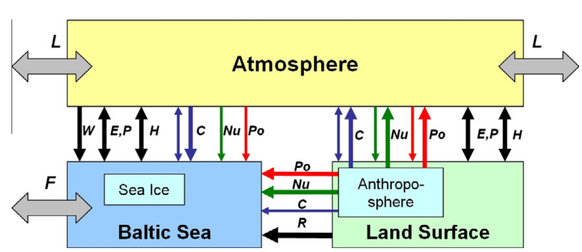

Fig. 2. The BALTEX box during Phase II (2003–2013) when water and heat balances, nutrients, and carbon cycles were included: *L* denotes lateral exchange with the atmosphere outside the region, *W* wind stress, *E* evaporation rate, *P* precipitation rate, *H* heat and energy fluxes, *R* river runoff, *F* inflows and outflows through the entrance area, *C* carbon fluxes, *Nu* nutrient fluxes, and *Po* pollutant fluxes (courtesy of Marcus Reckermann).

based on results from the BALTEX Phase II period, but also includes the results of other important programmes that have improved our understanding of Baltic Sea physics.

New datasets and tools

Over the past decade, the availability of data in the form of gridded datasets, long-term data series, and proxy data has improved greatly. This progress is based mainly on work carried out in the meteorological community, where several reanalysis products on decadal time scales are now available. Interestingly, work with reanalysis data started in the meteorological community in the late 1970s when modelling data were first being compiled. Several products were later developed that integrate observations and models in various ways. Global reanalysis meteorological datasets from NCEP (Kalnay et al., 1996; Saha et al., 2010), JMA (Onogi et al., 2007), NASA (Rienecker et al., 2011; Schubert et al., 1993), and ECMWF (Dee et al., 2011; Berrisford et al., 2011) are now available and have been used in many applications. During BALTEX I, a meteorological dataset with $1° \times 1°$ horizontal resolution was made available by the BALTEX Hydrological Data Centre, hosted by the Swedish Meteorological and Hydrological Institute (SMHI, http://www.smhi.se/sgn0102/bhdc/index.htm). Omstedt et al. (2005) compared the SMHI and the ERA-40 gridded meteorological datasets for the Baltic Sea region, both having $1° \times 1°$ horizontal resolution. These two datasets were demonstrated to be largely similar and both can be used in Baltic Sea modelling with reasonable accuracy. However, their horizontal resolutions were too coarse to resolve marine conditions over the Baltic Sea in detail. This implies, for example, that the ERA-40 surface winds are too low for certain Baltic Sea regions, so geostrophic winds and surface wind statistics had to be used instead, providing only a rough estimate of the wind field.

Precipitation data and heat flux components based on different types of observations were compared by Rutgersson et al. (2001, 2005), who supported the use of BALTEX I meteorological data with a $1° \times 1°$ horizontal resolution (but subject to a strong land influence due to the coarse resolution). The ERA-40 precipitation values were also too low compared with those of the SMHI $1° \times 1°$ data and other available data. Ruprecht and Kahl (2003) investigated the NCEP/NCAR reanalysis data, particularly those for the water balance over the Baltic Sea and its drainage basin, and found that they could not close the water balance. The main reasons for this failure were that the NCEP/NCAR precipitation values were too low over the studied region, and errors were obtained over mountainous regions due to the coarse resolution of the reanalysis dataset. SMHI later developed reanalysis data products with a higher horizontal resolution and, for example, ERAMESAN products are now available with a horizontal resolution of 11 km (for further details, see the Environmental Climate Data in Sweden portal, ECDS, at http://www.smhi.se/ecds). Höglund et al. (2009) analyzed winds over the Baltic Sea using ERA-40 data downscaled by the RCA 3.0 regional climate model (RCM) with a horizontal resolution of approximately 25 km. Even the downscaled wind data underestimated high winds, so the authors developed a statistical method to take this into consideration; however, the authors still claimed that it was necessary to improve boundary layer parameterizations and gridded data by using a higher horizontal grid resolution.

NOAA-CIRES have conducted a reanalysis covering the recent period from 1871 to 2008 (Compo et al., 2011). For periods several centuries long, gridded pressure and temperature datasets running from AD 1500 to the present have been constructed for Europe (Luterbacher et al., 2002, 2004). These data, together with other long-term datasets, have been used to characterize and model the Baltic Sea over the past 500 years: Eriksson et al. (2007) characterized the climate of the last 500 years (Fig. 3); Hansson and Omstedt (2008) modelled and analyzed temperature and sea ice conditions on a centennial time scale; Hansson et al. (2010) reconstructed river runoff to the Baltic Sea over the past 500 years; Hansson and Gustafsson (2011) examined oxygen and hypoxia dynamics; and Omstedt et al. (2009, 2010, 2012) examined the CO_2 balance and acidification of the Baltic Sea from preindustrial times to the future. In addition, high-resolution reconstructions of atmospheric surface fields, runoff, and nutrient loads for 1902–1998 (Kauker and Meier, 2003; Meier and Kauker, 2003a) and 1850–2006 (Gustafsson et al., 2012; Schenk and Zorita, 2012) were performed to force coupled physical–biogeochemical models of the Baltic Sea (Meier, 2006; Meier et al., 2011c, 2012c). Advanced statistical methods were employed in these reconstructions to guarantee homogeneous datasets. In the above studies, reconstructions of past Baltic Sea climate variability were often used also as a baseline for regional projections of the future climate up to 2100.

At the same time, great efforts have been made to reproduce the climate variation of the last thousand years or more. For example, the Past Global Changes (PAGES) 2k Consortium has recently published a number of continental-scale reconstructions of temperature over the past two millennia (PAGES 2k Consortium, 2013; these reconstructions are also available via the NOAA National Climatic Data Center, http://www.ncdc.noaa.gov/). More applicable to longer time scales are paleoclimate simulations for the past 8500 years by Gustafsson and Westman (2002) and for the past 1000 years by Schimanke et al. (2012). The latter used an RCM of Europe driven by global climate model results at the lateral boundaries and statistically reconstructed runoff to force a coupled phys-

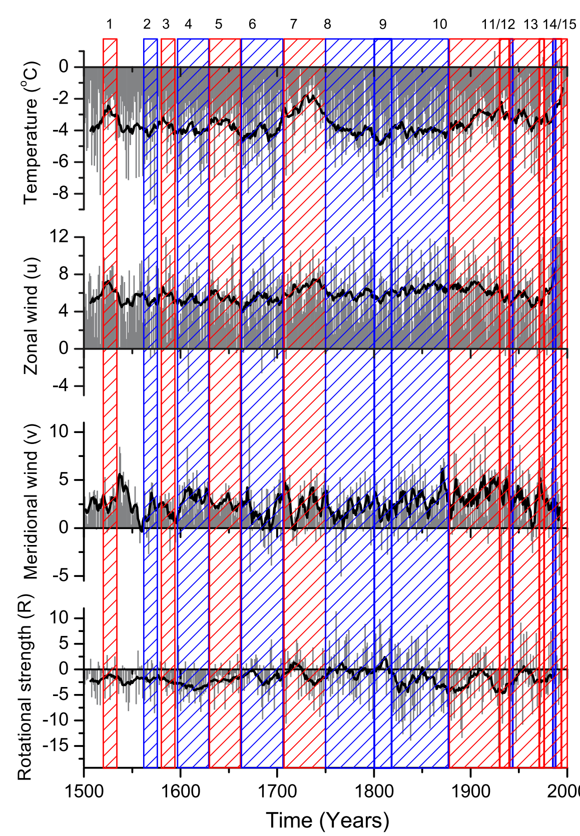

Fig. 3. Winter conditions of the past 500 years in the Baltic Sea region. The study identified 15 climate periods and they are illustrates as warm (red) or cold (blue) events (from Eriksson et al. (2007)). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

ical–biogeochemical model of the Baltic Sea to study water temperature, salinity, and oxygen conditions during the Medieval Warm Period and the Little Ice Age. Developments from early efforts to connect observations and models up to present efforts to generate reconstructions and gridded databases on up to millennial time scales have provided the research community with a wealth of freely available meteorological information. There is considerable potential to use these products in regional studies to improve our understanding of, for example, water and heat cycles. However, gridded data entail several problems that need to be considered when calculating statistical properties such as trends and extremes, as various measuring techniques are used to acquire the data.

Hydrological data, including for example river runoff to the Baltic Sea, are still difficult to access, so researchers must often rely on personal contacts with various national authorities. Data are available from several international initiatives, such as the BALTEX Hydrological Data Centre (http://www.smhi.se/sgn0102/bhdc/index.htm), the Global River Runoff Database (http://www.bafg.de/GRDC/EN/Home/homepage_node.html), and the River Discharge Database (http://www.sage.wisc.edu/riverdata/). These databases still cover only a few of the available river sites and are often not updated in timely fashion. It must be regarded as a major deficiency that data on such an important parameter for environmental and climate studies in the Baltic Sea region are not regularly updated and accessible to the research community.

In the last decade, oceanographic data have become much more accessible through, for example, the SHARK database at SMHI (http://www.smhi.se/k-data/marine_environmental_data.html) and through the International Council for the Exploration of the Sea (ICES, http://www.ices.dk/Pages/default.aspx). Janssen et al. (1999) developed data base for monthly mean temperatures and salinities from the North Sea and Baltic Sea region. A milestone of BALTEX Phase II was implementing the first regional reanalyses of the Baltic Sea using observations of water temperature and salinity together with high-resolution Baltic Sea models (Axell, 2013; Liu et al., 2013). For example, Liu et al. (2013) performed a 30-year reanalysis of temperature and salinity in the Baltic Sea using an ensemble optimal interpolation approach. However, most of the oceanographic data available in databases have coarse temporal and spatial resolutions. An interesting new platform is the FerryBox platform, which enables automated measurements and water sampling using ships of opportunity such as merchant vessels and passenger ferries (Ainsworth, 2008). FerryBoxes consist of suites of sensors that measure water variables such as temperature, salinity, carbon dioxide, oxygen, and chlorophyll a. The present FerryBox system in the Baltic Sea area includes approximately ten ships that regularly measure surface properties with a high spatial resolution of approximately 200 m and with a temporal resolution of about twice a day (Karlsson, 2012). The resulting datasets have provided the research community with new opportunities to study high-horizontal-resolution features such as fronts and other ocean processes with better temporal variation. One good example of the use of the FerryBox system is the study of the partial pressure of carbon dioxide and plankton bloom by Schneider et al. (2006), whose results are discussed in relation to modelling by Omstedt et al. (2014) (see Fig. 4). Other measurement platforms are also now available, such as the Östergarnsholm Station run by Uppsala University (Uppsala, Sweden), the Utö Station in the Turku archipelago run by FMI and SYKE (Helsinki, Finland), the MARNET stations run by the BSH (http://www.bsh.de/de/Meeresdaten/Beobachtungen/MARNET-Messnetz/MARNET.jsp), and the Darss Sill, Arkona Sea, and Oder Bay stations run by the Leibniz Institute for Baltic Sea Research (Warnemünde, Germany). These measuring sites form unique platforms for studies of high-temporal-resolution atmospheric and marine dynamics. However, only a few gridded oceanographic datasets are available. There is therefore a need for better cooperation between the modelling and observation communities to develop data- and model-screening methods and similar data-assimilation products as in the meteorological community. In addition, new initiatives to generate freely available ice datasets are needed, together with assessments of data quality.

It should also be mentioned that interesting new data portals and products are becoming available, such as the Climate Research Unit at the University of East Anglia (http://www.cru.uea.ac.uk/), the Climate Explorer at Koninklijk Nederlands Meteorologisch Instituut (KNMI, http://climexp.knmi.nl/start.cgi?id=someone@somewhere), Marinexplore.com (http://marineexplorer.org/), and MyOcean.eu (http://www.myocean.eu/). The first two portals make meteorological observation and model data and indices freely available. Marinexplore is an impressive portal for freely available global ocean data collected using several methods; this portal also provides data from the Skagerrak–Baltic Sea region. MyOcean provides products related to ocean monitoring and forecasting.

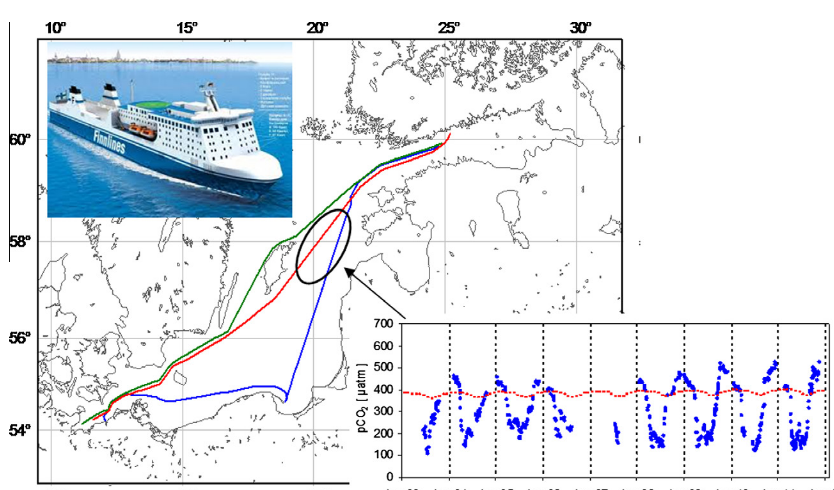

Fig. 4. Finnmaid making pCO_2 measurements on regular travels in the Baltic Sea. The pCO_2 measurements are indicated by blue dots and the corresponding measurements in the atmosphere by red dots (courtesy of Bernd Schneider). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The last decade has seen strong steps towards making observational and model data more accessible. This is a major achievement and should inspire additional efforts to improve observations and modelling and to develop transparent methods for quality control. The increasing amount of available information calls for new services providing expert guidance on data and model outputs before these are interpreted in management or research applications. For example, NCAR/UCAR has launched a climate data guide (https://climatedataguide.ucar.edu/) that combines data and leading expertise on the strengths, limitations, and applications of climate data. Another interesting example is the NOAA Bering Climate portal, which gives a current view of the Bering Sea ecosystem and climate (http://www.beringclimate.noaa.gov/index.html) in a pedagogic way.

Large-scale atmospheric circulation and the Baltic Sea

It is well known that large-scale atmospheric circulation over the European/North Atlantic region strongly influences Baltic Sea climate and environmental changes (e.g., Chen and Hellström, 1999), particularly in winter. The first mode of the principal component analysis of winter sea level pressure variability is the North Atlantic Oscillation (NAO) (e.g., Wallace and Gutzler, 1981). For the NAO positive (negative) phase, the Icelandic Low and the Azores High are enhanced (diminished), resulting in a stronger (weaker) than normal westerly flow (e.g., Hurrell, 1995; Hurrell and Deser, 2008). The NAO is defined for the European/Atlantic sector, but is part of the Arctic Oscillation atmospheric circulation pattern (see, e.g., Thompson and Wallace, 1998). The winter NAO index is closely correlated with both atmospheric and Baltic Sea properties (e.g., BACC II, in preparation; Chen and Hellström, 1999): a positive index indicates mild and wet winters, increased storminess (e.g., Wang et al., 2011), reduced sea ice (e.g., Omstedt and Chen, 2001; Vihma and Haapala, 2009), and a positive mean sea level anomaly (e.g., Andersson, 2002; Hünicke and Zorita, 2006), whereas a negative index indicates cold and dry winters. The NAO also influences the water mass exchange with the North Sea (e.g., Lehmann et al., 2002). Fig. 5a and c show the empirical orthogonal functions and the principal components corresponding to the winter NAO index from 1949 to 2011 (Chen et al., 2013).

The behaviour of the NAO can be fairly irregular for extended periods. However, from the mid 1960s to the mid 1990s, an apparent positive trend, i.e., towards more zonal circulation with mild and wet winters and increased storminess in central and northern Europe, was observed (e.g., Hurrell et al., 2003). Since then, however, a trend towards more negative NAO indices has been evident. The strongly positive NAO phase up to the mid 1990s is considered part of a multi-decadal pattern of variation rather than a trend towards more positive values (Jones et al., 1997; Moberg et al., 2005; Slonosky et al., 2000, 2001).

The second mode of the principal component analysis captures changes in the north–south location of the NAO and is called the East Atlantic pattern or Barents Oscillation (Wallace and Gutzler, 1981; Woolings et al., 2008). This is characterized by an anomaly in the north-eastern North Atlantic, between the NAO centres of action: negative values indicate the southward displacement of the NAO and lower temperatures (Moore and Renfrew, 2011), whereas positive values correspond to more zonal winds over Europe and expected higher temperatures. The blocking pattern over the Baltic Sea region is the third dominant mode of the principal component analysis and indicates an east–west shift of the northern centre of variability defining the NAO. It is called the Scandinavian pattern, Eurasian pattern (Wallace and Gutzler, 1981), or blocking pattern (Hurrell and Deser, 2008). In its positive

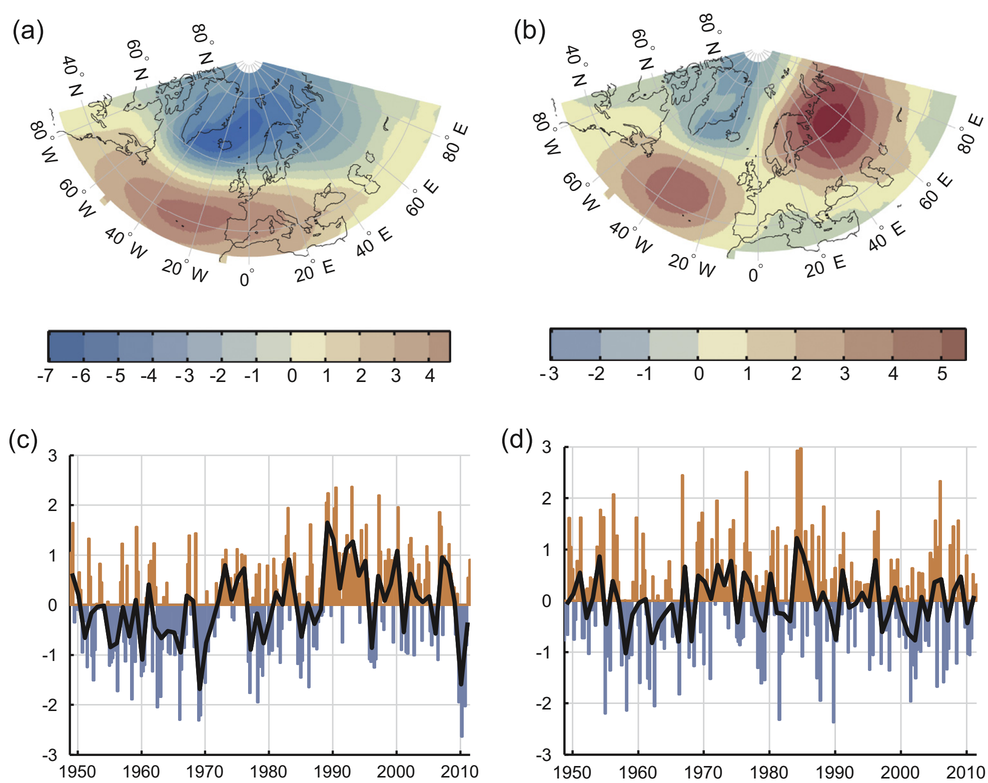

Fig. 5. Empirical orthogonal functions of monthly wintertime (DJFM) sea surface pressure anomalies (hPa) from 1949 to 2011 and the corresponding principal components. The patterns are associated with the (a) North Atlantic Oscillation, (b) Barents Oscillation, and (c and d) their time-varying indices. The black line in panels c and d shows the annual mean (from Chen et al. (2013)).

phase, it is characterized by a high pressure anomaly over Scandinavia and a low pressure anomaly over Greenland.

Recent decades have witnessed a north-eastern shift in low-pressure tracks consistent with a more zonal circulation over the Baltic Sea basin; this shift has been accompanied by intensified cyclonic circulation, with an increase in the number of deep cyclones (e.g., Bengtsson et al., 2006; Getzlaff et al., 2011; Kyselý and Huth, 2006; Lehmann et al., 2011). Blocking of the atmospheric flow is frequently observed in the Baltic Sea region. Blocking situations, which are often quasi-stationary and can persist for extended periods, are often responsible for extreme weather events. Rimbu and Lohmann (2011) constructed a North Atlantic blocking index indicating pronounced decadal variations and more frequent blocking in the 1910s, 1940s, 1960s, and after 1995, and low blocking particularly in the 1920s, 1970s, and early 1990s. Blocking is also related to the Barents Oscillation (Skeie, 2000), seen in Fig. 5b and d. There has been a general increase in the zonality of the flow in winter, though the opposite occurs in summer (Kaszewski and Filipiuk, 2003; Wang et al., 2009, 2011). Some studies demonstrate an increase in the persistence of weather types (Kyselý, 2000, 2002; Kyselý and Huth, 2006; Werner et al., 2000). For zonal, meridional, or anticyclonic circulations, increased persistence on the order of two to four days is found from the 1970s to the 1990s. This increase may be reflected in the increased occurrence of extreme events.

Circulation changes in the Baltic Sea region could also be related to climate anomalies at greater distances. Some studies (e.g., Overland and Wang, 2010) suggest a relationship between circulation changes in the European region and sea ice loss in the Arctic. Reduced summer sea ice results in increased heat release, contributing to an increase in the lower tropospheric relative topography (500/1000 hPa) and producing anomalous easterly winds in the lower troposphere along 60°N in many regions. The reduced summer sea ice extent might therefore result in circulation patterns resembling the negative phase of the NAO, and modelling experiments have tested this possibility. Petekouhov and Semenov (2010) performed a series of experiments using the ECHAM5 model and found that central European winter temperatures were dependent on sea ice cover in the Barents and Kara seas. A gradual decrease in sea ice cover from 100% coverage to ice-free conditions produced a strong temperature increase via a nonlinear relationship between convection over the ice-free parts of the Barents and Kara seas and baroclinic effects triggered by changes in temperature gradients near the surface heat source. Yang et al. (2011) used the higher-resolution EC-Earth model (Hazeleger et al., 2012) and confirmed a more linear decrease in winter temperatures with decreasing Barents and Kara sea ice cover than found by Petekouhov and Semenov (2010). Rutgersson et al. (2014), however, found relatively low correlation between Arctic summer ice data and near-surface winter temperatures in the Baltic Sea region over the 1851–2010 period. The relationship between reduced sea ice cover and cold North European winters has not been conclusively described (see, e.g., the review by Vihma (in press)). Based on a number of long-term datasets, Eriksson et al. (2007) were able to characterize the sub-arctic European winter climate over the past 500 years. They concluded that the climate could be characterized by centennial-scale variability and by the modulation of interannual and decadal signals, often accompanied by rapid shifts. There is little indication of major periodicities in the record, the Baltic climate being better characterized by discrete events. The apparent random initiation, variable event durations, and lack of "cycles" support the major influence of intrinsic variability on atmospheric climate.

Bengtsson (2013) further analyzed internal atmospheric variability over the past 500 years and found that the European near-surface temperature behaved in a predominantly stochastic fashion, but with indications of what can be interpreted as a superimposed warming trend appearing as the accumulation of the warmest seasons over the last two decades of the more than 500-year-long temperature record. Based on this, he stated that "the accumulation of extreme warm events can thus be seen as a falsification of true stochastic climate and lends strong support to the forcing from the well-mixed greenhouse gases, lacking other credible alternatives" (Bengtsson, 2013, p. 6).

Water and heat balances

The water and heat balances have been in focus throughout the BALTEX programme (Fig. 6) as they represent the heart of the climate system: It is impossible to understand the expected processes of change in the climate system without understanding the heat and water cycles and their interconnections. For example, we cannot understand changes in ocean salinity and sea level if we do not understand changes in the water balance. Likewise, we cannot understand sea ice cover and water temperature if we do not understand changes in the heat balance.

These cycles are interconnected via net precipitation (*P-E*) which has been a major BALTEX research topic. Smedman et al. (2005) reviewed several methods used to calculate *P-E* over a 12-month period, giving a best estimate of *P-E* over the Baltic Proper of approximately 100 ± 50 mm with indications of large interannual variations. Omstedt and Nohr (2004) examined the water and heat balances of the Baltic Sea based on gridded meteorological data from SMHI and on Baltic Sea modelling. In accordance with earlier studies, they demonstrated that the long-term net outflow through the Baltic Sea is in balance with river runoff and net precipitation over the sea area, and that other contributions to the water balance are less important. Their heat balance studies demonstrated that the long-term net heat loss through the Baltic Sea entrance area is small. Using ocean modelling as a tool in heat- and water-balance studies, it was possible, by comparing with independent water-temperature and salinity data, to estimate how accurately one could expect to calculate the long-term net water and heat balances. Other studies estimating long-term means of the different components were reviewed by Omstedt et al. (2004).

Studies of river runoff to the Baltic Sea have a long tradition in the Baltic Sea region, and earlier studies were summarized by HELCOM (1986). Bergström and Carlsson (1994) analyzed observed river runoff data for a 50-year period. Six years later, Cyberski and Wrobleski (2000) presented observed river runoff data for almost 100 years. Hansson et al. (2011) applied statistical downscaling and reconstructed river runoff to the Baltic Sea (Fig. 7) over the past 500 years using runoff observations from 1950 to

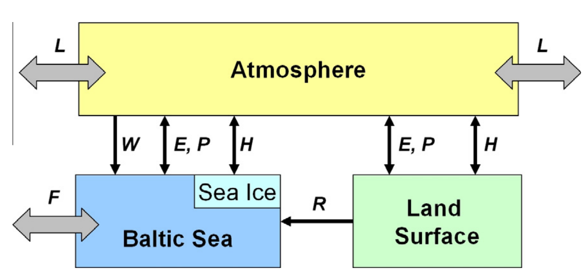

Fig. 6. The BALTEX box during Phase I (1993–2002) when water and heat balances were included: *L* denotes lateral exchange with the atmosphere outside the region, *W* wind stress, *E* evaporation rate, *P* precipitation rate, *H* heat and energy fluxes, *R* river runoff, and *F* inflows and outflows through the entrance area (courtesy of Marcus Reckermann).

1995 and reconstructed pressure and temperature data from Luterbacher et al. (2002, 2004). Runoff appears to be strongly linked to temperature, wind, and rotational atmospheric circulation components in the northern Baltic Sea and the Gulf of Finland, but is even more strongly linked to rotational and deformation atmospheric circulation components in the south. No significant long-term change has been detected in total river runoff to the Baltic Sea for 500 years, although decadal and regional variability is large. Analysis of runoff sensitivity to temperature indicates that the southern Baltic Sea may become drier with rising air temperatures. This is in contrast to the northern Baltic Sea and Gulf of Finland, where warmer temperatures are associated with more river runoff. Over the past 500 years, total river runoff to the Baltic Sea has decreased by 3% (450 $m^3\,s^{-1}$) per degree Celsius temperature increase. Recent observed trends in stream flow changes in the Nordic countries are discussed by Wilson et al. (2010). In general, strong annual positive trends are observed over the 1961–2000 year period, but not over the longer 1920–2005 period, illustrating the time period dependence of the results. A signal towards earlier snowmelt floods is clear, illustrating changes in the heat balance.

Omstedt and Hansson (2006a,b) analyzed the Baltic Sea climate system memory and demonstrated that two important time scales should be considered: one is associated with the water balance and has an e-folding time of approximately 30 years; the other is associated with the heat balance and has an e-folding time of approximately one year. These studies illustrate that, on an annual time scale, the Baltic Sea is almost in thermal balance with the atmosphere and that atmospheric changes will rapidly influence the sea ice and water temperatures. This can be illustrated by the Baltic Sea maximum sea ice extent, which is strongly related to winter conditions (Omstedt and Chen, 2001), and by the volume-mean observed water temperature, for which the auto correlation falls to 0.4 after one year (Omstedt and Hansson, 2006a,b). On the other hand, net precipitation over land and sea controls the Baltic Sea salinity, which changes on a decadal time scale. This can also be noted when studying the volume-mean salinity of the Baltic Sea, which fluctuates over a typical period of 30 years (Winsor et al., 2001, 2003). We thus expect that the effects of climate warming will first be observed in parameters related to the heat balance, such as water temperature and sea ice extent, and that it will take longer before they can be detected in parameters related to the water balance, such as salinity. This is also in good agreement with BACC assessments (BACC I, 2008; BACC II, in preparation), which have concluded that the present warming signal is limited to temperature and directly related variables, such as ice and snow conditions, and that water cycle changes will likely become evident later.

Jacob (2001) presented the first water budget calculation based on regional climate modelling and using reanalysis data as lateral boundary conditions. The calculated long-term water budget components were realistic, but further investigations of the physical parameterization of convection, snow melt, and runoff were needed. Bengtsson (2010) discussed the global atmospheric water cycle, including model simulation of the water balance of the Baltic Sea. Using reanalyzed ERA-40 data and regional climate modelling, the simulated water balance over a 10-year period was in close agreement with observations. Bengtsson (2010) also argued that when reliable river runoff data are available they could be used to validate the model-generated atmospheric hydrological cycle of a larger area. Large biases and inconsistent climate signals have been reported based on present state-of-the-art RCMs (e.g., Turco et al., 2013). Downscaling studies using RCMs still indicate a great need for improvement, as these studies often produce simulations that are too wet in the Baltic Sea region (BACC II, in preparation; Donnelly et al., 2014; Lind and Kjellström, 2009; Omstedt et al., 2000, 2012) and when impact studies are performed, bias corrections are needed when interpreting scenario runs.

Climate model scenarios display a tendency towards reduced salinities (Meier et al., 2012a), but the large bias in the water balance means that it is still uncertain how much salinity will actually change (BACC II, in preparation). Donnelly et al. (2014) analyzed calculated river discharge to the Baltic Sea based on new projections and hydrological modelling. In addition, they applied bias-correction methods but demonstrated that uncertainties in atmospheric projections, hydrological modelling, and bias corrections need to be investigated. Qualitatively, Donnelly et al.

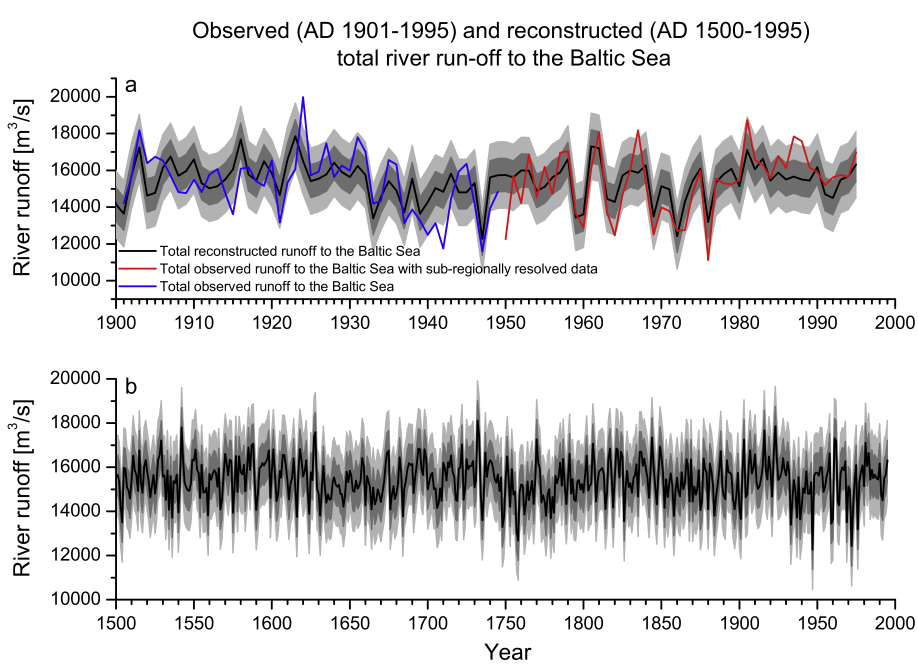

Fig. 7. Observed (blue and red lines) and reconstructed (black line) river runoff to the Baltic Sea (from Hansson et al. (2011)). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(2014) concluded that river inflow is likely to increase in the northern Baltic, but that it is still uncertain how it will change in the south. These uncertainties meant that it was difficult to draw conclusions about the magnitude of future change. Water cycle modelling in the Baltic Sea area could clearly benefit from additional research efforts.

Air–sea and air–ice interactions

The air–sea/ice interfaces constitutes complex systems of interaction mechanisms influencing the atmosphere, the sea and the ice. The higher heat capacity of the water surface than of the land surface and frequent large air–sea temperature differences (particularly over coastal regions) result in strong heat fluxes varying on a synoptic time scale. The sea surface changes in response to the forcing (i.e., surface waves), influencing the friction at the surface (i.e., momentum exchange and turbulence generation). Recent studies have demonstrated that surface gravity waves influence the exchange of momentum, and that in a relatively small basin with limited wave height, the swell effect leads to reduced surface stress. When introducing the impact of swell into models of the Baltic Sea, reduced wind stress was accompanied by reduced sensible and latent heat fluxes (Carlsson et al., 2009a,b). Fig. 8 shows the monthly mean difference between simulations including and excluding the wave impact when forcing a regional atmosphere model over the Baltic Sea area; the data comprise monthly mean fluxes and near-surface parameters for a five-year simulation. Reduced surface stress is expected to influence parameters in the atmosphere and ocean and to affect, for example, mixing in the surface water. In the presence of swell, the atmospheric turbulence indicates an increase in atmospheric mixing length scale and more efficient mixing in the atmosphere, resulting in decreased near-surface wind gradients (Nilsson et al., 2012; Rutgersson et al., 2012). The global research community has paid increasing attention to the impact of surface waves on mixing in the ocean, particularly in the case of the Langmuir turbulence (see Section 'Turbulence', Belcher et al., 2012).

It is therefore important to accurately describe the Baltic Sea wave climate, which, although milder than that of the open ocean, varies greatly in time and space. Fig. 9 shows the numerically simulated average significant wave height and its long-term (i.e., 1970–2007) change. Typically, long-term significant wave heights are approximately 1 m in the open sea in the Baltic Proper, with the greatest measured values exceeding 8 m in the northern Baltic Proper (Tuomi et al., 2011), though the measurement results depend greatly on the methodology used. Summer is typically the season with the smallest mean and maximum significant wave heights, whereas winter has the highest such values (excluding in seasonally ice-covered areas). The most frequent wave periods are 3–5 s over the open sea and 2–4 s in coastal areas (e.g., Soomere, 2008). Most combinations of wave heights and periods correspond to fully saturated wave fields in the northern Baltic Proper. The roughest seas, however, better match a fetch-limited wave spectrum characterized by shorter periods (BACC II, in preparation).

The turbulent air–sea exchange of heat and moisture is controlled by air–sea temperature and humidity differences and is strongly influenced by atmospheric stratification. Heat exchange declines significantly during stable atmospheric stratification, being particularly dominant in spring and early summer when the water is relatively cold (e.g., Rutgersson et al., 2001). One can expect upwelling regions to influence the net heat exchange, as these regions strongly influence the sea surface temperature and atmospheric stratification (see Section 'Upwelling'). Heat fluxes can be directly measured, but models or remote-sensing products are required for large areas. Rutgersson et al. (2005) compared various heat flux databases and demonstrated that the turbulent heat fluxes in the ERA40 reanalysis product were too large compared with measured values, mainly in winter, and that the downward sensible heat flux was overestimated in spring and summer as well. For the radiative fluxes, Rutgersson et al. (2005) found large

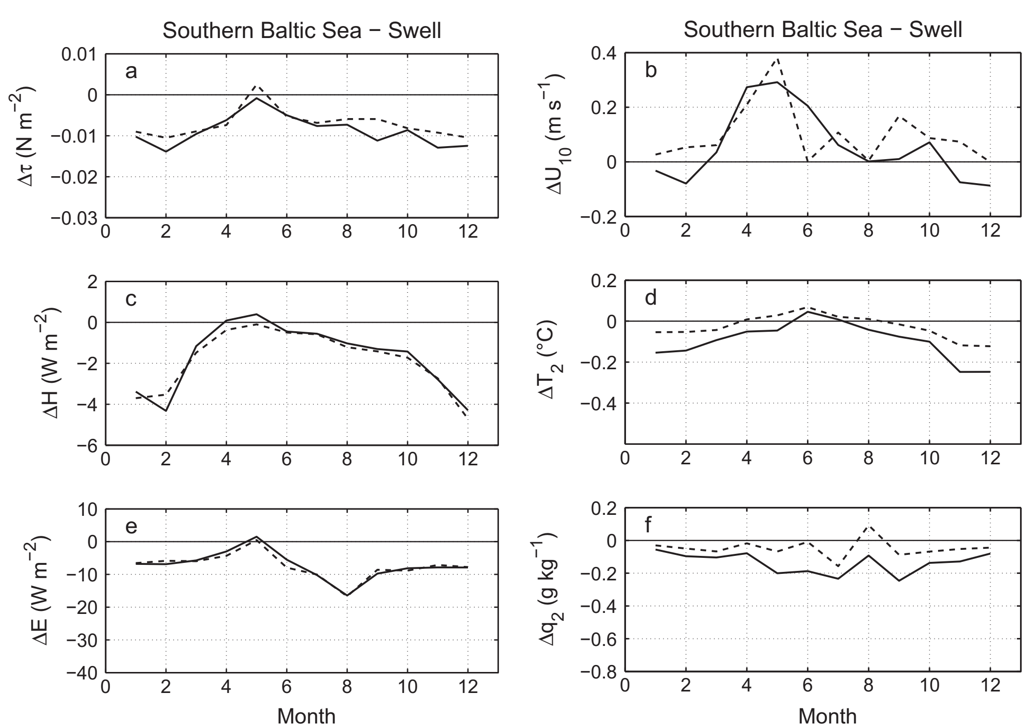

Fig. 8. Left: Monthly mean difference in turbulent fluxes. Left: wind stress, sensible heat flux and latent heat flux. Right: Low-level wind speed, temperature, and humidity under swell and unstable atmospheric stratification conditions. Thick lines represent simulations including reduced swell minus the reference run (using two versions of swell impact) (from Carlsson et al. (2009b)).

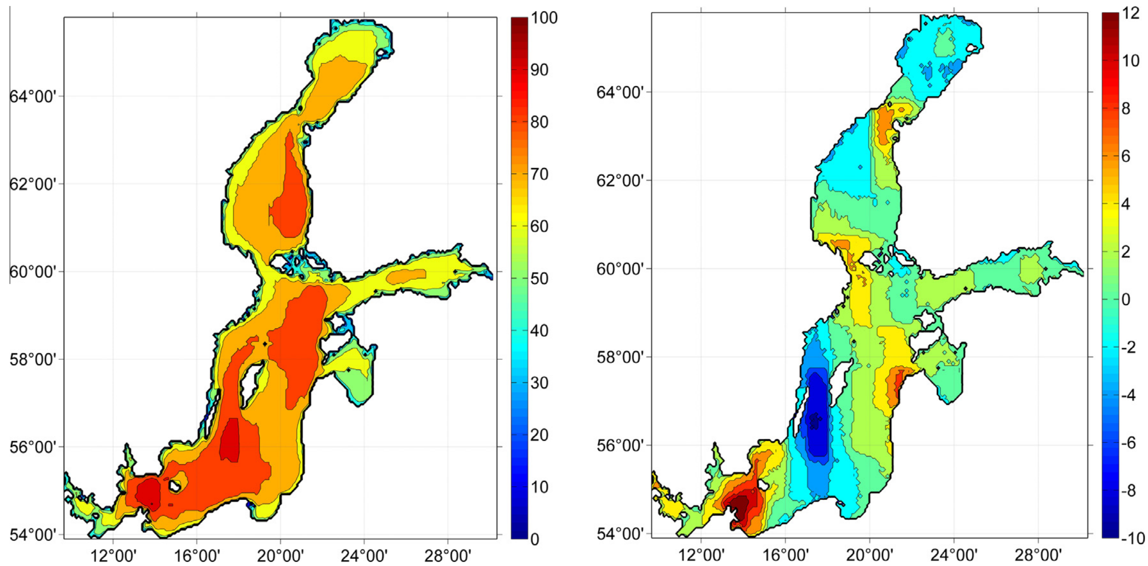

Fig. 9. Left: Numerically simulated average significant wave height (colour bar, cm; isolines plotted every 10 cm) in the Baltic Sea, 1970–2007 (from Räämet and Soomere (2011)). Right: Long-term changes in the annual average significant wave height (cm, based on the linear trend, isolines plotted every 2 cm), 1970–2007 (from Soomere and Räämet (2011)). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

differences between databases; however, considerable upward long-wave radiation was followed by considerable downward short-wave radiation, meaning that the total radiation component was partly compensated for in the total budget. Radiative fluxes are strongly linked to cloud cover, which decreased by 1% per decade over the 1970–2008 period (Lehmann et al., 2011) and may be reflected in the radiative heat flux components. Simulations of present (Omstedt and Nohr, 2004) and future (Döscher and Meier, 2004) climate, however, indicate that changes in the sum of the heat fluxes are relatively small in a changing climate, increased solar radiation being balanced by other heat fluxes. Fig. 10 shows the major components of the surface heat budget of the Baltic Sea sea/ice surface; even though the various components differ between simulations, their sum is small.

Air–sea exchange is strongly limited in the presence of ice, so small open areas (i.e., leads) contribute significantly to the exchange. Ice strongly affects the partitioning between heat flux components, but does not (in existing models) seem to significantly alter the net heat exchange over the entire Baltic Sea basin (Döscher and Meier, 2004; Omstedt and Nohr, 2004). The presence of ice, however, strongly influences a range of processes, including numerical weather forecasts (Drusch, 2006). Parameterizations of heat exchange between water and air still include a certain amount of uncertainty. When investigating turbulent surface momentum fluxes, sensible and latent heat, and surface mean parameters using a research aircraft over the marginal ice zone of the northern Baltic Sea, Schröder et al. (2003) demonstrated that ice surface heterogeneity strongly influences the surface heat fluxes and that many existing parameterizations result in overestimated fluxes. Brümmer et al. (2005) also demonstrated that cold and warm air advection over ice strongly influences the sensible heat flux. During the ice melt period, surface fluxes as well as surface albedo are strongly influenced by the rate of melting (Granskog et al., 2006; Pirazzini et al., 2006).

Sea ice physics

Baltic Sea ice

The Baltic Sea is a small oceanic basin containing brackish water. However, its ice is typical of seasonal sea ice zone (Leppäranta and Myrberg, 2009). The brine dynamics contribute significantly to the properties of Baltic Sea ice, and primary production is observed to occur in brine pockets in spring. The Baltic Sea is large enough that the ice cover breaks into floes, which drift when forced by winds and currents. The annual evolution and long-term climatology of Baltic Sea ice conditions have been fairly well explored (Leppäranta and Myrberg, 2009); in particular, geophysical sea ice questions related to winter shipping have a long research history. Sea ice forecasting commenced in the 1970s and satellite remote sensing was developed into the main tool for ice charting in the following decade. The scope of sea ice research expanded in the 1990s, in particular, to include climate

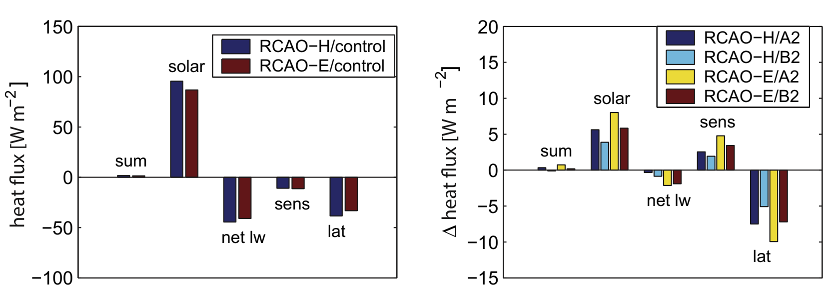

Fig. 10. Left: Overall mean heat flux from the atmosphere to the ice/ocean system and its components – shortwave ("solar"), net longwave ("net lw"), sensible ("sens"), latent ("lat"), and the sum of all components. Right: Differences between heat fluxes of the scenario and control experiments (scenario/control) (from Döscher and Meier (2004)).

change impacts (Haapala and Leppäranta, 1996; Haapala et al., 2001; Jevrejeva et al., 2004) and sea ice ecology (Ikävalko, 1997). Since year 2000, sea ice in the coastal zone has become established as an important line of research.

Sea ice and society is a key issue, since approximately 85 million people live in the Baltic Sea drainage basin (e.g., Lépy, 2012). Sea ice influences everyday life in the frozen part of the Baltic Sea as well as fisheries, shipping, marine engineering, and economic life. A series of Baltic Sea Ice Climate Workshops was initiated in 1993 and is repeated every three years. This series has proven to be an excellent resource for Baltic Sea ice scientists.

Coastal zone

In the near-shore zone, which includes depths of less than approximately 10 m, Baltic Sea ice appears as land-fast ice, while drift ice fields are found farther out. The coastal sea ice zone covers the region from the shoreline to the boundary of land-fast ice and drift ice. It interacts directly with the land and the drift-ice field, and there is often a discontinuity in ice motion at the drift ice boundary. The coverage of land-fast ice changes the upper surface boundary condition by reducing the influx of turbulent shear, weakening the heat loss to the atmosphere, and reducing the exchange of matter between the atmosphere and the water body. As most of the coastal zone is shallow, it has received little research attention, which has been directed by the needs of winter shipping.

The land-fast ice zone serves as a very good platform for field studies of ice and its underlying water. In this zone, the ice structure evolves from freshwater to sea ice types. Ice properties have been extensively investigated in the land-fast ice of the Gulf of Finland (Granskog et al., 2004, 2006; Kawamura et al., 2001). The freshwater ice type occurs only in estuaries, where the salinity of the surface water is less than 1.5‰ (Kawamura et al., 2002). The land-fast ice sheet consists of congelation ice and snow-ice. The growth and decay of land-fast ice is well understood and good models of it are available (Cheng et al., 2003; Saloranta, 2000).

A solid ice cover weakens circulation and turbulence. When river inflow is significant, the water body becomes salinity stratified beneath the ice, where inflowing river water forms a freshwater layer. Merkouriadi et al. (2013) analyzed the year-round heat budget of a coastal site in the Baltic Sea, and Merkouriadi and Leppäranta (2013) examined the interaction between the coastal region and open sea in the western Gulf of Finland (Fig. 11). These studies were based on observational records and fill a major gap in our empirical knowledge of Baltic Sea physics.

Land–ice interaction has recently attracted renewed attention and become a major issue due to new coastal and offshore infrastructure construction and nature protection (Fig. 12). It was first investigated in the 1800s but only sporadically thereafter. Land–ice interaction includes bottom scouring, shore modification, ice forcing, and the shore ride-up and pile-up of ice (Girjatowicz, 2004; Leppäranta, 2013; Orviku et al., 2011).

Fig. 12. Ice ride-up on the shore of Hailuoto, Finland, on 19 December 1992 (courtesy of Markku Tönkyrä, Hailuoto).

Ice erosion is an important ecological factor in the Baltic Sea. The shores of the northern Gulf of Bothnia are home to a few species of vascular plants whose communities can survive only on shore areas where ice erosion regularly removes larger plants and bushes, and migrating and nesting birds also need shores and rocks cleaned by the action of sea ice. The principal erosion mechanisms are the wind-driven shore ride-up and pile-up of ice, and ice growth down to the sea bottom with resulting transport of bottom sediment when the ice drifts out to sea. The former mechanism is also a risk to structures built too close to the shoreline.

Ice charting and ice dynamics

All Baltic Sea countries have ice information services that produce ice reports and charts on a daily basis. Ice mapping has developed into a user-friendly system with ice charts and forecasts available on the Internet. Remote-sensing methods have been developed to improve the quality of ice information services (e.g., Karvonen, 2004, 2013; Karvonen et al., 2005; Leppäranta and Lewis, 2007; Mäkynen and Hallikainen, 2005). The main question that remains to be answered by remote sensing is that of sea ice thickness. Limited information on ice thickness can be obtained using various methods, but the overall results are unsatisfactory; this problem is common worldwide.

Sea ice drift is an essential factor in the evolution of ice conditions and a major issue in ice forecasting. In recent years, knowledge of Baltic Sea ice dynamics has improved (Leppäranta, 2011). Detailed spectral analysis of ice drift has been performed by Leppäranta et al. (2012), including high frequencies. The use of downscaling methods to evaluate local forces from mesoscale geophysical sea ice models has been ongoing and shown some prom-

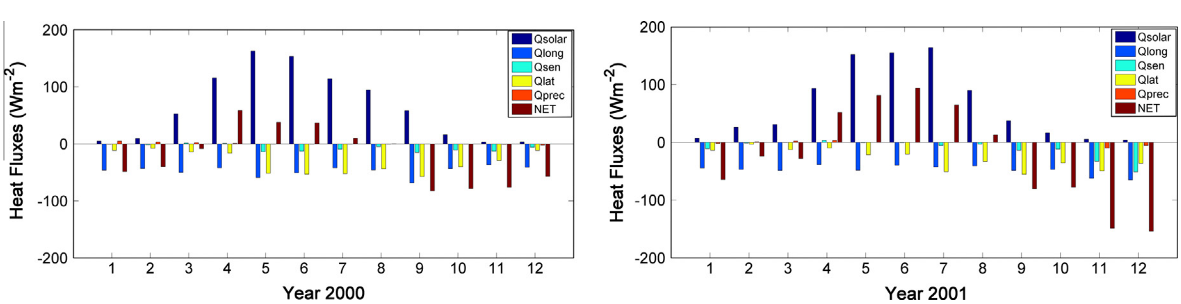

Fig. 11. Monthly average heat flux components for (a) 2000 and (b) 2001 (from Merkouriadi et al., 2013).

ise (e.g., Kõuts et al., 2007; Pärn and Haapala, 2011; Wang et al., 2003, 2006). Goldstein et al. (2009) examined the dynamics of sea ice at the boundary of land-fast ice and drift ice (Fig. 13).

Ice and environmental questions

Surface water freezing has environmental impacts in the Baltic Sea (Kaartokallio, 2005; Rintala, 2009; Rintala et al., 2009). The northern Baltic Sea freezes regularly, while in the central southern

Type of mechanical action	Forcing	Type of structure	Scale of structure (km^2)	Boundary conditions
1.Uniform tension	Intensive wind loads	a-const. System of parallel faults	10^4	Free boundary
2. Uniform tension	Wind loads	a-const. Echelons of parallel (linklike) faults	10^3	Free boundary
3.Bi-axial tension	Wind loads (spreading of the high pressure region)	Concentric fault system	10^4	Free boundary
4. Uniform compression	Wind loads	ridge Conjugate structures compression tension fault	10^4	Shore line perpendicular to wind
5.Shear loads	Loads of under the ice current	Rotational structures of faults and ridges	10^3	Free boundary

Fig. 13. Classification of large- and meso-scale ice-cover structures based ice fracture mechanics (Goldstein et al., 2009). Columns 1 and 2 show forcing and type, column 3 shows structural patterns identifiable in airborne or spaceborne remote-sensing data, and columns 4 and 5 show scale and boundary types.

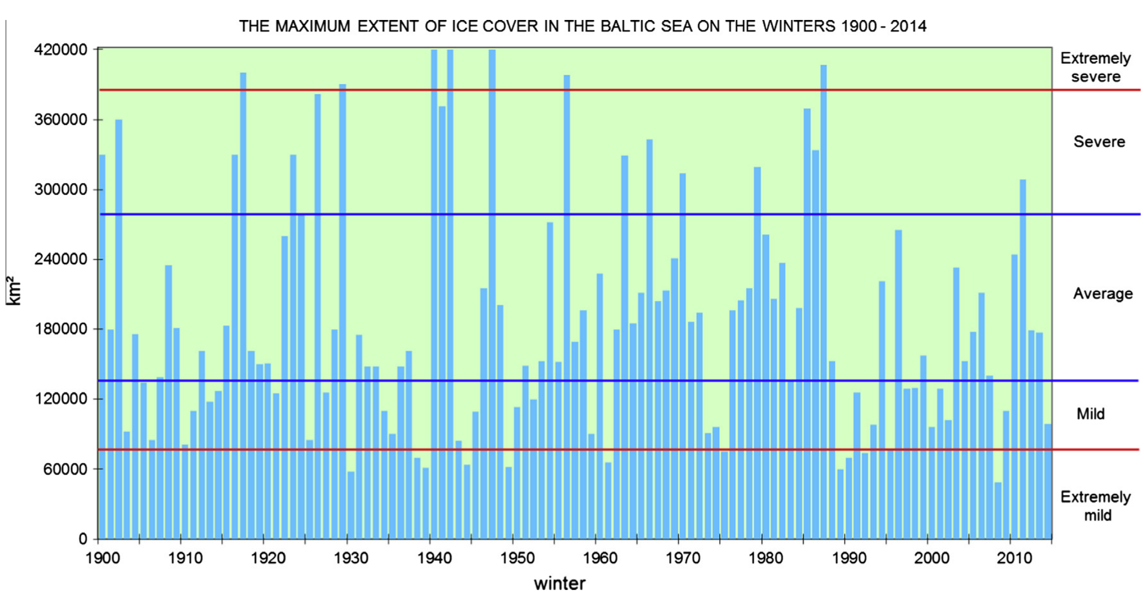

Fig. 14. Maximum annual ice extent in the Baltic Sea (prepared by Jouni Vainio, Finnish Ice Service).

basins, the probability of freezing is below 10%, so ice occurrence is extremely rare. Fig. 14 shows a time series, starting in 1720, of the maximum annual ice extent, illustrating the very large variability. The time series indicates a weak decreasing trend, aperiodic variations, and a high noise level.

Atmospheric fallout accumulates in the ice sheet in winter, and impurities are captured from the water body and sea bottom during ice formation. These substances are transported by the ice and released to the surface water layer in the melting season. This transport also affects sedimentation on the sea bottom. The risk of oil spills under specific ice conditions is a major issue (Wang et al., 2008). The brackish ice of the Baltic serves as a growth habitat for ice algae, as does normal sea ice. The future of Baltic Sea seals is also dependent on the quality of future ice seasons.

Light transmission through ice and the light conditions underneath ice have been investigated by Arst et al. (2006), who found that the albedo was 0.28–0.76 and the light transmittance was 1–52%. The light field below the ice was much more diffuse than under open water conditions, and the euphotic depth was estimated to be 0.1–5.5 m. Brackish ice is much less transparent than lake ice because of internal brine pockets with their resident algae populations.

A time series of estimated annual maximum ice extent starting from 1720, initiated by Risto Jurva (Palosuo, 1953) and available at the Finnish Meteorological Institute (Fig. 14), has been widely used in Baltic Sea ice climate investigations. Hansson and Omstedt (2008) analyzed and validated the Jurva time series in an independent model study, bolstering confidence in these data. Historical documents support model estimates before 1719 and yield information on maximum ice extent from 1500 to the present. Jevrejeva et al. (2004) examined the evolution of ice seasons in the Baltic Sea in the 20th century; data from a number of sites were combined using fractiles of the distribution since stations with different ice occurrence probabilities had to be compared. The time series provides evidence of a general trend towards easier ice conditions, best seen in the length of the ice season, which has decreased by 14–44 days per century. The probability of ice occurrence has significantly decreased in the southern Baltic Sea. Jaagus (2006) examined the ice season trends along the Estonian coast, and sea ice projections for future climate change scenarios are discussed by the BACC I and II author teams (2008, in preparation). Merkouriadi and Leppäranta (2013) have examined the joint long-term time series of hydrography and ice conditions on the coast of the Gulf of Finland.

Turbulence

Widely used parameterizations for Baltic Sea modelling (e.g., the $\kappa-\varepsilon$ or $\kappa-\omega$ sub-models for vertical mixing and the Smagorinski formulation for horizontal mixing) are quite often chosen and tuned based on data from the open oceans (where the stratification conditions differ greatly from those in the Baltic Sea) or are extracted from laboratory experiments that only partially replicate the complexity of the marine environment. Choosing the proper parameter values for the numerical scheme still remains a major challenge for Baltic Sea modelling. There is a long-term approximate advective–diffusive balance in the deep water (Stigebrandt, 2001), as advective supplies of new deep water tend to increase and diffusive fluxes tend to reduce the salinity. However, this is not in balance on shorter time scales due to the discontinuous nature of the advective supply of deep water. Since tides are usually small in the Baltic Sea, most of the energy to sustain turbulence in the deep-water pools must be provided by the wind. An important recent review by Reissmann et al. (2009) summarizes the various mixing mechanisms operating in the Baltic Sea. Although many of these processes are already described in hydrodynamic models, one that is typically missing is the effect of surface waves, exerted directly through the breaking of surface waves and indirectly through Langmuir circulation (Tuomi, 2014).

Basic parameterization

Stigebrandt (1987, 2001) has concluded, based on the results of long-term modelling of the large-scale vertical circulation in the Baltic Proper, that under contemporary conditions, the basin-wide vertical diapycnal diffusivity (or diapycnal mixing coefficient) in the deep-water pools can be reasonable well described by:

$$\kappa = \min\left(\frac{\alpha}{N}, \kappa_{\max}\right) \tag{1}$$

where α and $\kappa_{\max}$ are constants and N is the Brunt-Väisälä frequency. In his horizontally integrated model of the Baltic Sea proper, Stigebrandt (1987) tuned α to equal $2 \times 10^{-7}\ \mathrm{m^2\,s^{-2}}$. According to Meier et al. (2006a), α depends on energy fluxes from local sources, such as breaking internal waves, wind-driven inertial currents, Kelvin waves, and other coastally trapped waves. This means that mixing near coasts and topographic slopes is more thorough than in the open sea. Axell (1998) found, based on measurements, that $\alpha = 1.5 \times 10^{-7}\ \mathrm{m^2\,s^{-2}}$ and that it varies seasonally as well. For $N = 10^{-2}\ \mathrm{s^{-1}}$, we have $\alpha/N \sim 1.5 \times 10^{-5}\ \mathrm{m^2\,s^{-1}}$, while the normal level in the mixed layer is 10^{-3}–$10^{-2}\ \mathrm{m^2\,s^{-1}}$, which serves as a reference for $\kappa_{\max}$. In the process-oriented and 3D numerical models, the above mixing coefficient parameterization is usually added to the coefficient derived from the turbulence sub-models.

Mechanisms of diapycnal mixing

Considering the balance of turbulent kinetic energy, turbulence production by vertical current shear is balanced on average by kinetic energy loss via its dissipation ε (which can be estimated from the measured microstructure profiles) and via buoyancy flux due to the mixing. Osborn (1980) has found a relationship between the dissipation rate and buoyancy flux, allowing estimation of the upper bound of mixing coefficient values. Further studies by Gargett and Holloway (1984) revealed that, within the field of single-frequency internal waves, the dissipation rate is proportional to the Brunt-Väisälä frequency, resulting in expression (1) However, values of mixing coefficients estimated from the basin-wide budgets tend to be larger than those estimated based on spatial and temporal details (e.g., Axell, 1998). Of the internal waves, the near-inertial period (approximately 14 h) often dominates the water column motions. In the DIAMIX (DIApycnal MIXing) project, Lass et al. (2003) measured dissipation rates and stratification at depths of 10–120 m during a nine-day experiment in the Eastern Gotland Basin. Their main finding was that there are two well-separated turbulent regimes. The turbulence in the surface layer, as expected, was closely connected to the wind. However, in the strongly stratified deeper water, turbulence was fairly independent of the meteorological forcing at the sea surface. The integrated production of turbulent kinetic energy exceeded the energy loss from inertial oscillation in the surface layer, suggesting that additional energy sinks might have been inertial wave radiation during the geostrophic adjustment of coastal jets and mesoscale eddies. Stigebrandt's (1987) diapycnal mixing coefficient, α, was estimated to be $0.87 \times 10^{-7}\ \mathrm{m^2\,s^{-2}}$, less than earlier estimates based on bulk methods. Van der Lee and Umlauf (2011) have recently demonstrated, based on massive experimental data, that the major energy fraction of near-inertial waves is generated on the lateral slopes of basins; in agreement with earlier rough estimates, they conclude that most diapycnal mixing takes place near the slopes. This result was independently confirmed by the BATRE tracer experiment (see Section 'Tracer and Lagrangian studies'). Deep water ventilation in the Baltic Sea is very limited due to the pronounced vertical stratification, especially due to the existence of a halocline. Water masses with different temperature–salinity relationships are created by intruding "new" waters from the upstream basin or formed locally by slope-intensified mixing. In such a situation, so-called thermohaline intrusions can play an important role. These intrusions, which are closely linked to fluxes of heat, salt, and momentum injected laterally into the vertical profile, are ubiquitous in the ocean and occur in a variety of processes, but often most strongly near ocean fronts. Though often expected to be created by double-diffusive flux divergences, a number of processes can generate the lateral pressure gradient needed for these intrusions. These processes include the differential mixing of temperature and salinity and the symmetric instability of gravity-driven current dynamics (Alford and Pinkel, 2000).

Zhurbas and Paka (1997, 1999) proposed two mechanisms of deep-water ventilation in the Baltic Sea Proper: (1) continuously inflowing gravity-driven dense bottom flows filling the deepest layers, and (2) intermittent cyclonically rotating eddies in the halocline, eroded laterally by intrusions. Based on measurements, Zhurbas and Paka (1997) found that thermohaline intrusions, coupled with the similar effects of mesoscale eddies, play an important role in deep-water ventilation. The propagation of inflowing water farther into the Baltic Sea is accompanied by intensive intrusive layering in the permanent halocline.

Other mixing aspects

One major large-scale mixing process is the episodic overflow of water over the sills into the Baltic Sea, forming dense bottom currents and leading to the entrainment and interleaving of the incoming water masses to the level of neutral buoyancy (e.g., Lass and Mohrholtz, 2003). Through this mechanism, the Baltic Sea deep waters are ventilated (e.g., Meier et al., 2006a). Because of volume conservation, this process leads to the uplift of water masses in the central Baltic. Winter-time convection, wind-induced entrainment, and diapycnal mixing in the deep layers should balance the kinematic uplift of halocline on longer time scales (see, e.g., Leppäranta and Myrberg, 2009). Coastal upwelling and downwelling (Lehmann and Myrberg, 2008) play important roles in the wind-forced mixing of thermocline and sub-thermocline waters.

Surface waves affect the vertical mixing directly through wave breaking and indirectly through Langmuir circulation (e.g., Smith, 1998). The effects of surface wave breaking are usually thought to penetrate to depths of only a few metres in the surface layer, and are often considered in terms of the wind-speed-dependent (not wave-dependent) friction velocity. Kantha and Clayson (2004) have demonstrated (see also the Baltic Sea study of Kantha et al., 2010) that the Stokes production of turbulent kinetic energy in the mixed layer is of the same order of magnitude as is the shear production and must therefore be included in mixed-layer models (Fig. 15). Stokes drift together with mean shear generate Langmuir cells. Taking Langmuir circulations into account in vertical turbulence schemes affects the deepening of the mixed layer (e.g., Kukulka et al., 2010; Ming and Garrett, 1997). Although the small size of the Baltic Sea limits the growth of surface waves, the waves are high enough to be significant even in the small sub-basins of the Baltic Sea (e.g., Soomere and Räämet, 2011; Tuomi et al., 2011). Summer is typically the season with the lowest mean and maximum values of significant wave height and winter the

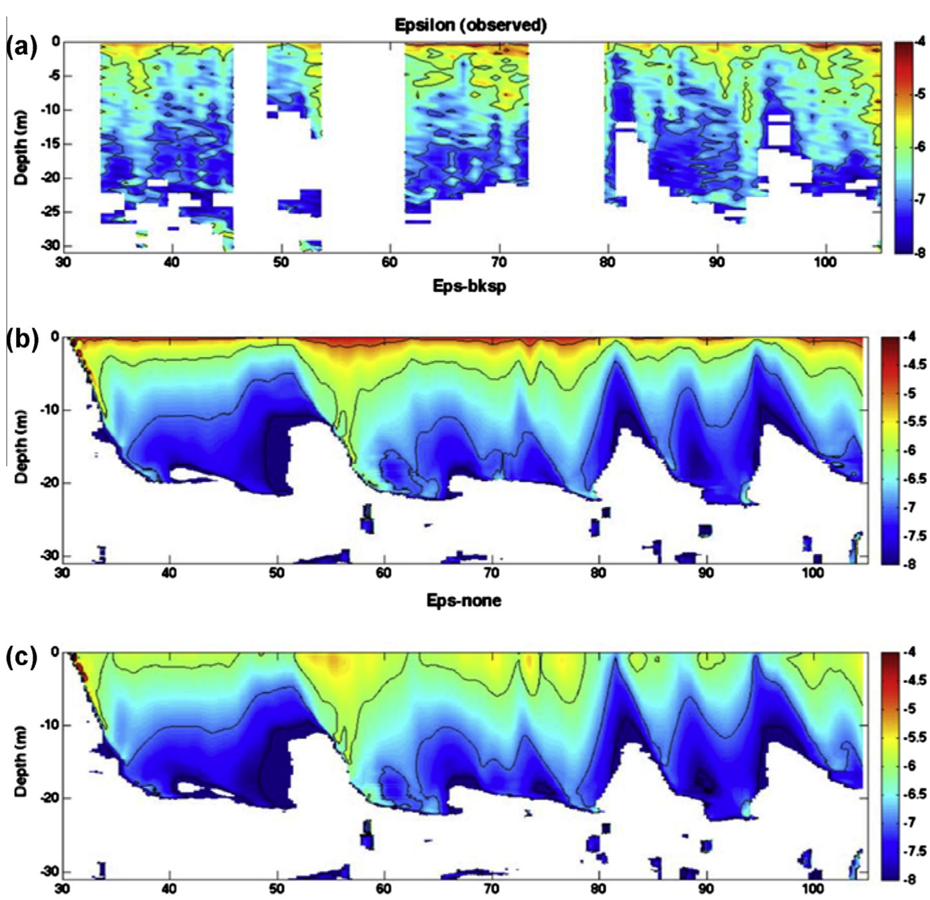

Fig. 15. Turbulent kinetic energy dissipation rate (in W kg^{-1}): (a) observed by microstructure measurements in the Bornholm Basin; (b) modelled with wave breaking and Stokes drift; and (c) modelled with wind dependence only (from Kantha et al. (2010)).

season with the highest such values (excluding in seasonally ice-covered areas). Axell (2002) has demonstrated the importance of including the parameterization of internal waves and Langmuir circulations in the vertical turbulence schemes in multi-year simulations of the Baltic Sea.

Tracer and Lagrangian studies

New features of surface Lagrangian transport have been found in three areas, i.e., the Gulf of Finland, Baltic Proper, and south-western Baltic Sea. There is strong seasonal variability in the Gulf of Finland and the possibility of rapid transport across the Gulf (towards the coasts); remarkably, there may be an anticyclonic gyre in the central and eastern parts of the Gulf (Soomere et al., 2011a). Lagrangian surface transport has been found to be asymmetrical towards the coasts of the Baltic Proper, and the probability of tracers hitting the coast is much greater along the eastern coast than at the same distance from the western coast (Lehmann et al., 2014). The same holds true for the time it takes tracers to reach the coast and for the quasi-Eulerian transport (Höglund and Meier, 2012). In the south-western Baltic Sea, the properties of Lagrangian surface transport towards the coast are determined mostly by the overall flow regime, coastal hits occurring relatively frequently during inflow phases but rarely during outflow phases (Lu et al., 2012).

The properties of spreading passive tracers at the sea surface (0–1 m) in the Gulf of Finland and of Lagrangian transport in a subsurface layer (12–18 m) in the Baltic Proper were established using surface and subsurface drifters (Kjelsson and Döös, 2012). Two regimes of surface layer spreading were found in the Gulf of Finland, one for small distances and another for distances of a few hundred metres. The parameters of both regimes can be established in terms of power laws (Soomere et al., 2011c).

An interesting deep-water tracer experiment, the Baltic Sea Tracer Release Experiment (BATRE), was conducted in the Gotland Basin (Holtermann and Umlauf, 2012; Holtermann et al., 2012). As one of its main results, vertical mixing rates were found to increase dramatically after the tracer had reached the lateral boundaries of the basin, suggesting boundary mixing to be the key process of basin-scale vertical mixing. It takes several months before tracer patches with sharp boundaries become conflated with the surrounding water. Turbulent boundary layers are thick and permanent in the deep parts of the flat-bottomed basins. Slopes have an intermittent turbulence regime because of their restratification tendency. Boundary mixing is enhanced by damped basin-scale topographic waves with a period of a few days and by deep rim currents; to a lesser degree, near-inertial waves also help generate boundary mixing on the slopes.

How turbulence parameterizations affect model results

Tuomi et al. (2012) used the 3D hydrodynamic Coupled Hydrodynamical Ecological model for Regional Shelf Seas (COHERENS) to study the accuracy of vertical turbulence schemes for calculated temperature and salinity using the Gulf of Finland as a test area. The vertical turbulence schemes used were the algebraic schemes of Pacanowski and Philander (1981) and Munk and Anderson (1948) as well as the $\kappa - \varepsilon$ model and the *k*-model. Three sets of stability functions were used in the *k*-model. The *k*-model was run both with and without limiting conditions for the mixing length. The conclusions can be summarized as follows. The algebraic parameterizations of vertical turbulence by Munk and Anderson (1948) and Pacanowski and Philander (1981) achieved the best accuracy for the calculated salinity profiles. The best accuracy for temperature and the thermocline depth was achieved using the *k*-model with stability functions based on Munk and Anderson (1948) formulations, but without limiting conditions for the mixing length. The selection of stability functions significantly affected the accuracy of the turbulence closure schemes. Only small differences in accuracy were observed between the $\kappa - \varepsilon$ model and the *k*-model when they used the same stability functions. Generally better accuracy was achieved with the *k*-model when the mixing length limiting condition was not applied. All vertical turbulence schemes underestimated the depth of the mixed layer. The sensitivity of the turbulence parameterizations to the forcing wind speed indicated that an increase in the wind speed used to force the model positively affected the accuracy of the thermocline depth calculation. However, the effect was relatively small compared with the existing underestimation of the thermocline depth. Similar studies were presented by Omstedt (2011), who tested various models using the PROBE equation solver. For multiple-year simulation, algebraic schemes such as those of Pacanowski and Philander (1981) obviously do not hold, as they neglect changes in wind. However, the $\kappa - \varepsilon$ model and the *k*-model produce more realistic results if they also include parameterizations for deep-water mixing.

Dynamics of straits and deep channels

General flow features

The Danish Straits – the narrow and shallow Öresund, Great Belt, and Little Belt – impose significant constrictions on the water exchange between the Baltic and North seas. In the stratified Baltic Sea, there are also at least 14 sills critical to the vertical separation of the water exchange (Leppäranta and Myrberg, 2009). Besides the entrance area sills, shallow connections are also found from the Baltic Proper to the Gulf of Riga and to the Bothnian Sea, blocking the paths of deep sub-halocline waters into these basins. The major areas of the Baltic Sea differ distinctly in salinity, water colour, and/or other water properties, usually exceeding the range of corresponding variations within the basins. This basic Baltic Sea feature has justified the extensive use of time-dependent models of vertically resolved connected basins, as pioneered by Stigebrandt (1987) and Omstedt (1990). In the last ten years, such models have been used extensively for a variety of purposes, ranging from climate change studies to the evaluation of possible ecological engineering solutions (Gustafsson and Omstedt, 2009; Gustafsson et al., 2012; Hansson and Gustafsson, 2011; Hansson and Omstedt, 2008; Hjalmarsson et al., 2008; Omstedt et al., 2009, 2010, 2012; Stigebrandt and Gustafsson, 2007; Stigebrandt and Kalén, 2012; Savchuk, 2005), including applications in smaller coastal embayments (e.g., Arneborg et al., 2004; Engqvist and Stenström, 2009; Hansson et al., 2012; Pastuszak et al., 2005; Stigebrandt and Liljebladh, 2011). Such connected-basin models clearly need adequate formulae for calculating exchange flows in the straits and channels, based on the modelled basin-averaged state variables.

The straits of the Baltic Sea have often been divided according to their dominant dynamic features into the two flow regime classes: mostly shallower straits with barotropic (i.e., non-layered) flow and straits with baroclinic (i.e., layered by water column density) flow. Although the actual flow in a specific strait is characterized by a combination of these regimes (Stigebrandt, 1980), depending on the time scale under consideration, one regime may strongly dominate. The barotropic flow regime typically dominates in the Danish Straits, as demonstrated early on by Svansson (1959) and others. In such a flow regime, the driving pressure gradient (due to sea level and air pressure changes) and local wind forcing are mostly balanced by friction. The straits are narrow compared with the barotropic Rossby deformation radius (a few hundred km), so inflow variations with a time scale of less than a week and rotational effects such as flow balance by Coriolis-parameter-dependent terms (as in geostrophic relationships) do not dominate. On longer times scales, the baroclinic flow component is usually also important (e.g., Jakobsen et al., 2010).

On the other hand, average flow conditions in several deep passages, such as the Bornholm Strait and Stolpe Channel, are often treated as baroclinic, in which pycnocline and layered flows exist more or less permanently. A two-layer approach is normally used in theories considering the flow speeds u_1 and u_2 in layers of thickness h_1 and h_2 separated by a density jump, $\Delta\rho$, which is small compared with the reference density, ρ. The phase speed of long internal waves in the case of no background motion is expressed as $c = \sqrt{g'h_*}$, where $g' = \frac{g\Delta\rho}{\rho}$ is the reduced gravity and $h_* = \frac{h_1 h_2}{h_1+h_2}$ is the effective layer thickness. Based on the Bernoulli principle applied to a frictionless two-layer flow, the composite Froude number, Fr (e.g., Armi, 1986; Pratt and Whitehead, 2007), can be written as:

$$Fr^2 = \frac{u_1^2}{g'h_1} + \frac{u_2^2}{g'h_2} \tag{2}$$

At the morphometric constriction of the "flow tube" (i.e., horizontal capes and/or vertical sills), the actual flow speed of water particles, u, may increase from the normal oceanographic regime to such a high value that the Froude number, $Fr = \frac{u}{c}$, reaches or exceeds the critical value of $Fr = 1$. At the location of the critical value $Fr = 1$, the interface between the layers usually drops rapidly from one level to another; long internal waves cannot pass this location, so mixing/energy loss takes place. The condition $Fr = 1$ determines the magnitude of maximal exchange flow, which depends on the strait geometry/width, g', and the elevation, η_∞, of the interface layer depth in the far upstream basin (usually assumed to be large and deep) above the sill level. A rotational hydraulics approach accounting for the Coriolis parameter, f, holds for wide channels, compared with the baroclinic Rossby deformation radius, $R_d = \frac{c}{f}$; the along-channel frictionless flow is then in geostrophic balance. Many of the Baltic Sea connected basin models referred to earlier use the following transport formula derived by Whitehead et al. (1974):

$$Q_{\max} = \frac{g'\eta_\infty^2}{2f} \tag{3}$$

whereas the transports are usually tuned by adjusting the sill depths. Borenäs and Lundberg (1988) elaborated on theoretical flow characteristics of a channel with a parabolic cross-channel depth profile: $H(y) = H_0 + \alpha y^2$. The maximal exchange volume transport corresponding to $Fr = 1$ is:

$$Q_{\max} = \eta_\infty^2 \left(\frac{3g'}{2\alpha}\right)\left(2 + \frac{f^2}{g'\alpha}\right)^{-1} \tag{4}$$

Obviously, the non-rotating version of expression (4) is obtained for narrow straits when $\frac{f}{\sqrt{g'\alpha}} \ll 1$. The transport expression (4) or its extensions have been used for realistically interpreting flows in a number of straits and deep channels: the Bornholm Strait (Laanearu and Lundberg, 2000), Stolpe Channel (Borenäs et al., 2007), Understen–Märket trench between the Åland and Bothnian Sea (Hietala et al., 2007), and Irbe Strait between the Baltic Proper and the Gulf of Riga (Laanearu and Lundberg, 2003; Laanearu et al., 2000).

Flow examples from specific study cases

In a recent study of the Baltic Sea entrance area, Jakobsen et al. (2010) demonstrated that in the Great Belt the barotropic exchange flow driven by sea level difference is well balanced by the quadratic friction, as anticipated earlier. However, the specific resistance with an average value of $41.2 \times 10^{-12}\ s^2\ m^{-5}$ depends strongly on the seasonally varying position of the density interface. The baroclinic flow component is small in magnitude but, due to its persistent direction, it accumulates most of the transported heat, salt, and materials. In two-layer situations, Lund-Hansen et al. (2008) have demonstrated that flow speeds in the bottom layer of the Little Belt may reach and even exceed the critical values for the hydraulic control criteria. These critical flow regions in the middle of the strait are characterized by higher mixing reflected by 30% higher primary production; high near-bottom nutrient levels remaining after the spring bloom indicate the strong net import of deep water from the Kattegat surface layers. The salinity of imported Kattegat waters depends on the circulation and frontal dynamics of that region and on the intermittent outflows of the brackish Baltic Proper water; Nielsen (2005) identified previously unknown occasional strong anticyclonic circulation. Further studies using numerical modelling (e.g., Bendtsen et al., 2009) have demonstrated that interannual variations of mixing and dense water ventilation in the Belt Sea area cause corresponding changes in deep-water properties in the western Baltic.

Intensive oceanographic studies were conducted in the Kriegers Flak (e.g., Lass et al., 2005; Sellschopp et al., 2006), a channel-like constriction in the western Baltic Sea. A gravity flow approximately 10 km wide and 10 m thick was found to be sub-critical in terms of the Froude number and significantly influenced by bottom friction, with an Ekman number of about one (Umlauf and Arneborg, 2009a,b). The cross-channel density structure was found to be

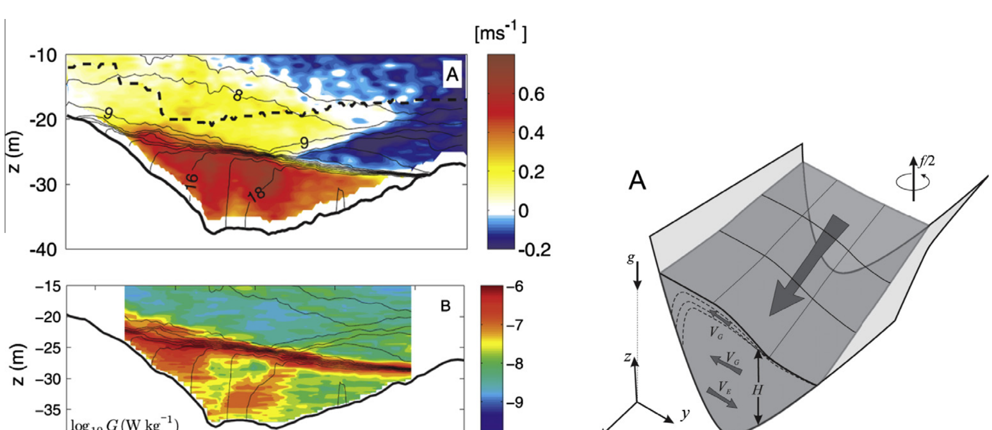

Fig. 16. Flow in the Kriegers Flak region, western Baltic: (a) down-channel flow speed and density (above) and vertical buoyancy flux (below); (b) conceptual scheme of rotational sub-critical gravity current with transverse Ekman flow and an interfacial jet (from Umlauf and Arneborg (2009a,b)).

asymmetric: the downward bending of isopycnals on the right-hand slope can be explained by transverse Ekman circulation and an interfacial jet; the flow scheme was confirmed by direct current measurements (Fig. 16). Umlauf and Arneborg (2009a,b) explained that this transverse Ekman transport is balanced by the geostrophic transport due to the down-channel tilt of the interface. The dynamics of gravity currents in the western Baltic, including the Bornholm Strait, have also been investigated in a series of numerical model studies (Burchard et al., 2005, 2009).

Zhurbas et al. (2012) analyzed a large dataset of high-resolution observations of the Stolpe/Słupsk Channel from 1993 to 2009, capturing a variety of cross-channel density patterns. The initial hypothesis that the density pattern variability is caused by variable wind forcing, either contributing to or preventing the eastward overflow (Krauss and Brügge, 1991), was not confirmed. Numerical experiments revealed that the flow can be described as a sub-critical eddy-producing gravity current in a wide channel, including friction effects. Density variations are caused by the meandering of the gravity current and by mesoscale eddies – mostly above-halocline cyclones and intra-halocline anticyclones. In this light, it is not surprising that Borenäs et al. (2007) concluded, when applying formulae (2) and (3) in a steady rotational hydraulics approach, that this theory is of limited use when dealing with the observed overflow; they instead offer explanations referring to the average overflow rates.

Green et al. (2006) examined the flow and mixing regimes in the Northern Kvark connecting the Bothnian Sea to the farther-from-the-ocean Bothnian Bay via two channels. Observations revealed significant temporal intermittency of the flow regimes (Fig. 17). Approximately 45% of the time, the flow was barotropically blocked, meaning that barotropic flows due to sea level gradients are strong enough to block the gravitational flow, resulting in the presence of only one layer in the strait. For the remaining 55% of the time, the flow was characterized either by a two-layer or continuously stratified regime. Under these conditions, the flows were on average hydraulically controlled ($Fr \approx 1$), although both lower and higher Fr values may occur.

The Gulf of Finland is connected to the Baltic Proper without a sill or horizontal constriction; however, several features of flow variability in the western and central Gulf are characteristic of wide channels (Elken et al., 2011). Recent observations by Liblik et al. (2013) indicate that persistent strong south-west winds in winter create anti-estuarine transport, which causes stratification collapse and the oxygenation of bottom layers. When the south-west winds cease, stratification and hypoxia are rapidly restored. Although the stratification collapse resembles barotropic blocking of the two-layer flow, the authors believe that longitudinal density gradients and wind-induced strain (i.e., differential along-channel advection) are important in creating temporary unstratified flow regimes.

Upwelling

Introduction

As the Baltic Sea is a semi-enclosed, relatively small basin, winds from virtually any direction blow parallel to some section of the coast and cause coastal upwelling. During the thermally stratified period, upwelling can lead to a strong sea surface temperature (SST) drop of more than 10 °C within just a few days, drastically changing the thermal balance and stability conditions at the sea surface (see, e.g., Lehmann and Myrberg, 2008). Upwelling can also play a key role in replenishing the euphotic zone with the nutrients necessary for biological productivity when the surface layer is depleted of them. In general, two classes of upwelling can be distinguished, open sea and coastal upwelling, the latter being discussed here.

Upwelling as a meso-scale feature is scaled by the baroclinic Rossby radius. As thermal stratification varies seasonally in response to solar heating and wind-induced mixing in the Baltic Sea, the baroclinic Rossby radius varies by 2–10 km (Alenius et al., 2003; Fennel et al., 1991) – less than in the oceans in general.

How atmospheric forcing is coupled with upwelling

Accurate descriptions of the wind, temperature, and humidity fields are essential for studying upwelling dynamics. According to Ekman's (1905) theory, alongshore winds are the most effective at generating upwelling in large basins, because the resulting surface layer motion induced over a wide sea area occurs in a relatively narrow area of rapidly varying depth. The occurrence of upwelling also depends on the stratification and strength of the wind impulse. Therefore, the initial stratification conditions before an upwelling takes place largely determine the needed wind impulse (see, e.g., Myrberg et al., 2010a); for modelling purposes, for example, accurately describing the stratification conditions strongly determines the success of the upwelling simulations.

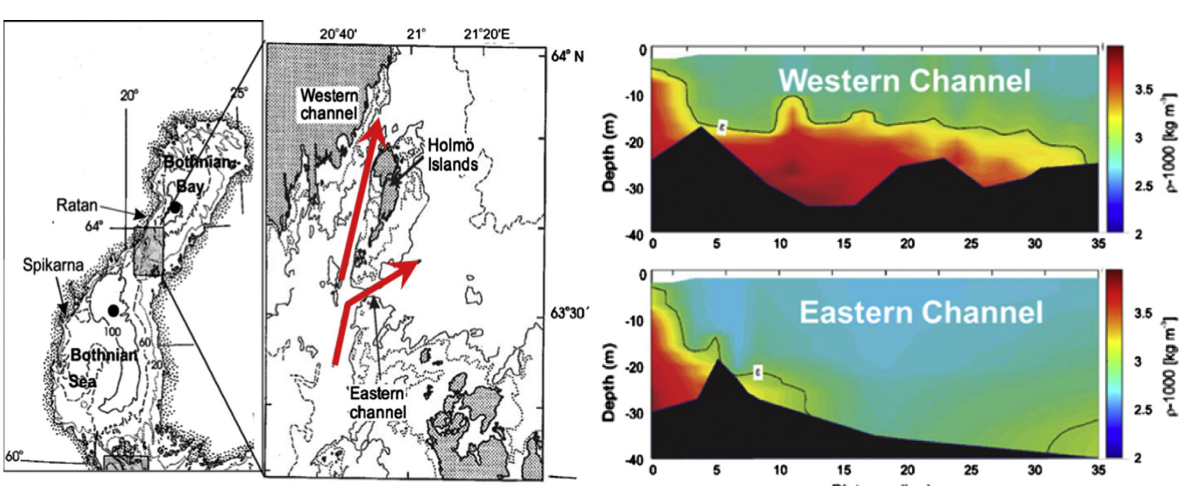

Fig. 17. Dynamics of the Northern Kvark: (a) map of the region and (b) density transects from south to north through the Western Channel (above) and Eastern Channel (below) (redrawn from Green et al. (2006)).

In the Baltic Sea area, different general weather conditions favour upwelling in different coastal areas. Bychkova et al. (1988) identified 22 typical areas in various parts of the Baltic Sea that were favourable for upwelling in relation to 11 different wind conditions (Fig. 18). Lehmann et al. (2012) conducted a long-term wind analysis based on 3060 daily mean wind fields for the months of May to September over the 1990–2009 period. A frequency of 10% corresponds to 306 days of upwelling-favourable winds. The highest frequencies – up to 30% favourable wind conditions – appeared along the Swedish south and east coasts, off the southern tip of the island of Gotland (approximately 15%), and on the Finnish coast of the Gulf of Finland (14%). The overall agreement of upwelling frequencies with favourable wind conditions was very high (see Lehmann et al., 2012, for details).

The temporal development of upwelling events along the Baltic Sea coast was calculated from the time series of upwelling frequencies (443 weeks for May–September in 1990–2009). Generally, there is a positive trend in upwelling frequencies along the Swedish coast of the Baltic Sea and the Finnish coast of the Gulf of Finland and a negative trend along the Polish, Latvian, and Estonian coasts. This is in line with the warming trend of annual mean air temperatures and mean SSTs derived from infrared satellite images from 1990 to 2008 (Lehmann et al., 2011). The smallest trends, i.e., 0.3–0.5 °C decade^{-1}, occurred along the east coast of Sweden, compared with 0.5–0.9 °C decade^{-1} in the central Baltic Proper. Lehmann et al. (2011) postulated that the decrease in the warming trend along the coast was due to increased upwelling connected with a shift in the dominant wind directions. The trend

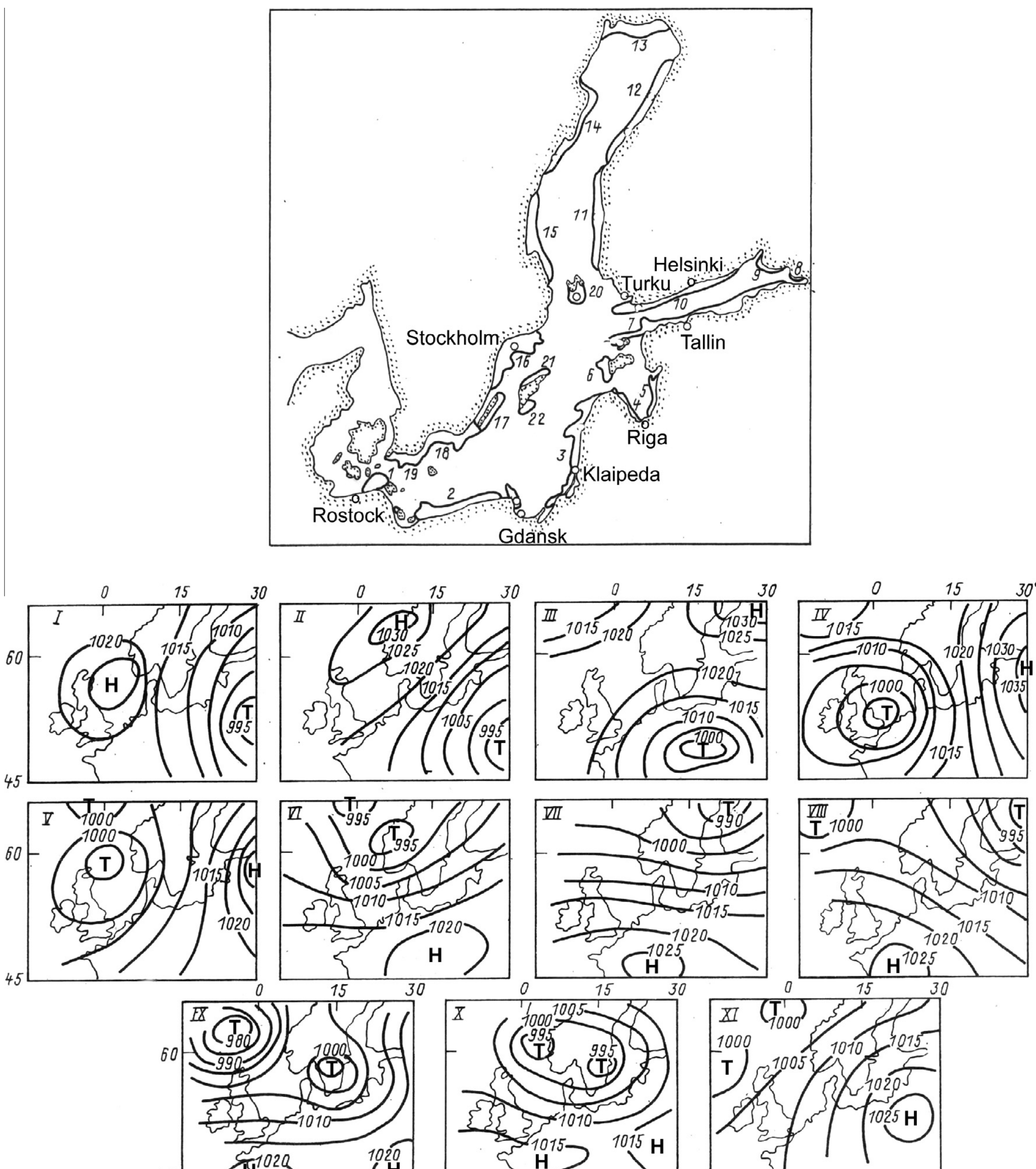

Fig. 18. Top: Common upwelling zones in the Baltic Sea (Bychkova et al., 1988). Bottom: Eleven typical atmospheric conditions that favour upwelling in different areas of the Baltic Sea (from Leppäranta and Myrberg (2009)).

analysis of favourable wind conditions derived from the wind station data from May to September for the 1990–2009 period supports this hypothesis (Lehmann et al., 2012). There is a positive trend of south-westerly and westerly wind conditions along the Swedish coast of the Baltic Sea and the Finnish coast of the Gulf of Finland and a corresponding negative trend along the east coast of the Baltic Proper, the Estonian coast of the Gulf of Finland, and the Finnish coast of the Gulf of Bothnia.

New results based on satellite images and modelling

Lehmann et al. (2012) studied May–September upwelling events from 1990 to 2009 using both satellite images and 3D modelling. They found that upwelling events occurred most frequently along the Swedish east coast and the Finnish coast of the Gulf of Finland. Upwelling frequencies were related to prevailing wind conditions during particular months and to the orientation of the coastline with respect to the wind direction. Upwelling frequencies were high, up to 25–40% on the south and west coasts of Sweden and up to 20–25% on the northern coast of the Gulf of Finland (Fig. 19), in line with the modelling results of Myrberg and Andrejev (2003). Locally, upwelling can cover very large areas of a water basin: Uiboupin and Laanemets (2009) demonstrated that up to 38% of the surface area of the Gulf of Finland could be covered by upwelling.

Zhurbas et al. (2006, 2008) used a very-high-resolution model of the Gulf of Finland and found meso-scale features of upwelling, filaments, and squirts. The various phases of the upwelling process were later explained in detail by Gurova et al. (2013) based on case studies of the east coast of the Baltic Sea in which joint modelling results and satellite data were combined to study upwelling dynamics. The authors found that the upwelling can be divided into two phases. In the first phase, the active phase, the wind is strong, the sea level tilt reaches its maximum, and the cold water reaches the surface. In that stage, the coastal jet is mostly barotropic. This jet is controlled by vorticity dynamics related to variations in the flow direction. Decreasing water depth leads to a situation in which the jet is deflected from the coast, whereas increasing water depth causes it to return to the coast. In the second phase, the relaxation period, the wind has weakened but a strong density (temperature) gradient persists, the sea level tilt has already decreased, and the flow field is now determined mainly by a baroclinic coastal jet, which may become baroclinically unstable with squirt and filament formation.

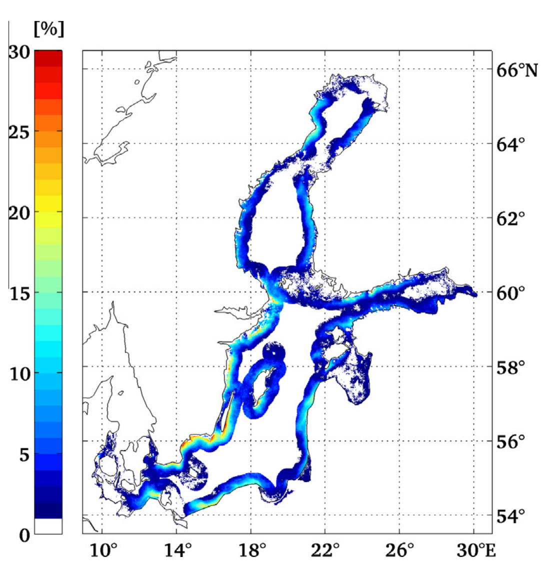

Fig. 19. Upwelling frequencies (%) from May to September obtained using the automatic detection method and a 2 °C temperature threshold, based on 3060 BSIOM (Baltic Sea Ice–Ocean Model, Kiel) SST maps, 1990–2009.

Biological and chemical implications

The effects of upwelling on late-summer cyanobacterial growth have been investigated in detail by Vahtera et al. (2005). Phytoplankton growth in the Baltic Sea is usually nitrogen limited, an exception being the growth of filamentous cyanobacteria, which fix atmospheric nitrogen. Cyanobacterial growth, however, is phosphorus and temperature limited. The effects of upwelling on cyanobacterial blooms are not straightforward, due to the decreased temperature in upwelling regions and to potential changes in the dissolved inorganic nitrogen:dissolved inorganic phosphorus (DIN:DIP) ratios. Coastal cyanobacterial and phytoplankton dynamics have recently been observed to be affected by upwelling by other authors as well (Lips and Lips, 2008, 2010). According to Laanemets et al. (2004), high nutrient concentrations occur near the thermocline, at least in the Gulf of Finland. They demonstrated that the vertical transport of phosphate and nitrate by upwelling and turbulent mixing depends on the separation of the phosphacline and nitracline. A clear ordering of seasonal nutraclines in the pycnocline/thermocline was observed with increasing depth, i.e., silicacline, phosphacline, and nitracline. As upwelling leads to phosphorus enrichment and low DIN:DIP ratios in the euphotic layer, filamentous nitrogen-fixing cyanobacteria might benefit from the phosphorus enrichment (cf. Niemi, 1979). Zhurbas et al. (2008) calculated that the Redfield (i.e., N:P) mass ratio, normally 7.2, can be as low as 0.093 due to upwelling. A clear excess of phosphorus coming to the surface during upwelling has been reported, for example, by Laanemets et al. (2011), who found that the bottom slope also plays an important role in upwelling. Upwelling can also considerably alter the CO_2 flux between sea and air. During coastal upwelling, cold water from below the thermocline brings high-CO_2 water masses to the sea surface. Upwelling can therefore reduce the annual uptake of CO_2 in the Baltic Sea by up to 25% (Norman et al., 2013).

Other sub-basin processes

The Baltic Sea is famous for the transient nature and great variability of the patterns of its driving forces (Lehmann et al., 2011), the extreme complexity of its marine environment dynamics, its very small internal Rossby radius (Alenius et al., 2003; Fennel et al., 1991), the chaotic appearance and low directional persistence of its surface currents (Andrejev et al., 2004a), and its complicated drifter paths (Döös and Engqvist, 2007).

Since the 1980s, remote-sensing results (Horstmann, 1983) and dedicated in situ measurements (e.g., Aitsam et al., 1984) have indicated the existence of mesoscale eddies in the Baltic Sea. However, the spatial and temporal extent of these eddies and their role in circulation remained unestimated until the last decade due to lack of high-resolution modelling tools and relevant measurements. Recent analysis of currents simulated with a horizontal resolution of one nautical mile revealed that surface currents in the Gulf of Finland are mostly strain dominated rather than vorticity dominated (Viikmäe et al., 2012) and contain a very limited number of clearly identifiable eddies (Viikmäe and Torsvik, 2013). In contrast, Karimova (2012), who studied 978 synthetic aperture radar (SAR) images from 2009 to 2010, identified 6234 spiral eddies manifested in the surface roughness. This analysis indicates that the sea surface eddies are predominantly cyclonic, appear everywhere except in archipelagic regions, and are generally 1–10 km in diameter. Regarding water-column eddies, Reissmann

(2005) applied a pattern-recognition algorithm to data from 12 mesoscale CTD surveys conducted in the MESODYN project in the four deep basins of the Baltic Sea. He found that, on average, 12% of the sea volume is contained in density anomalies constituting single mesoscale eddies. These various views suggest that our knowledge of mesoscale and sub-mesoscale eddies needs further development.

There is increasing model-based evidence of the existence of ordered patterns of currents in the Baltic Sea, such as frequently repeating pathways of single particles (Döös et al., 2004) and water masses (Meier, 2007) or highly persistent flows in certain layers (Andrejev et al., 2004a,b). The properties of such semi-persistent patterns and the predominant directions in current-driven transport in the surface layer have been addressed using both Eulerian and Lagrangian modelling. The Eulerian framework was used to evaluate the long-term advection patterns of selected water parcels in the surface layer throughout the Baltic Sea (Höglund and Meier, 2012), while a similar framework for the Gulf of Finland involved modelling the direct impact of wind on such parcels (associated with persistent particles of neutrally buoyant pollution) (Murawski and Woge Nielsen, 2013). The Lagrangian framework was implemented by statistically analyzing up to 20-day-long trajectories of purely current-driven advection of selected water parcels (Soomere et al., 2011a), mostly in the framework of quantifying the potential of various offshore areas to serve as starting points for coastal pollution (Soomere et al., 2011b, 2014).

The basic scalar properties of the net transport speed (equivalent to the average current speed) calculated based on the output of the RCO model (Meier et al., 2003) with a horizontal resolution of two nautical miles and using the non-spreading TRACMASS code (see Döös et al., 2013, for an overview) mostly match existing knowledge. The surface layer flow in the central and western Gulf of Finland, however, only somewhat resembles the classical cyclonic circulation scheme. For example, modelling indicates the existence of a large anticyclonic gyre in 1987–1991 in the velocity fields of the central and eastern Gulf (Fig. 20). Such structures usually appear when the upper mixed layer is very thin (Beletsky et al., 2006). This feature suggests that the motions in the surface layer may be largely decoupled from the dynamics of the underlying water masses.

In the Gulf of Finland, the patterns of average net transport speed differ considerably between seasons, especially during windy and calm periods (Soomere et al., 2011a). The total drift (i.e., current-driven advection plus wind-induced drift) of parcels in the surface layer, however, largely matches the pattern found in the windy winter and calm summer seasons (Murawski and Woge Nielsen, 2013). Most areas hosting rapid net transport are located along the coasts and evidently reflect coastal currents. Several areas of relatively fast cross-gulf net transport appear during transitional seasons (Fig. 21), suggesting that surface water masses may frequently be rapidly transported towards the coast in this gulf.

Lagrangian trajectory statistics indicate that purely current-driven advection in the Gulf of Finland and the Baltic Proper is asymmetric, i.e., water parcels are more likely to drift towards the southern or eastern near shore of these water bodies (Andrejev et al., 2011; Höglund and Meier, 2012; Lehmann et al., 2014). This feature essentially mirrors the asymmetry of Ekman transport, which is driven by prevailing south-westerly winds mostly to the east or south-east. This asymmetry has implications for the choice of environmentally friendly sailing routes: if the goal is to minimize the current-driven propagation of adverse impacts from the fairway to the near shore (or to maximize the time taken for these impacts to reach the coast), the optimum fairway should be located mostly to the west of the axis of the Baltic Proper (Höglund and Meier, 2012; Lehmann et al., 2014) (Fig. 22) or to the north of the axis of the Gulf of Finland (Andrejev et al.,

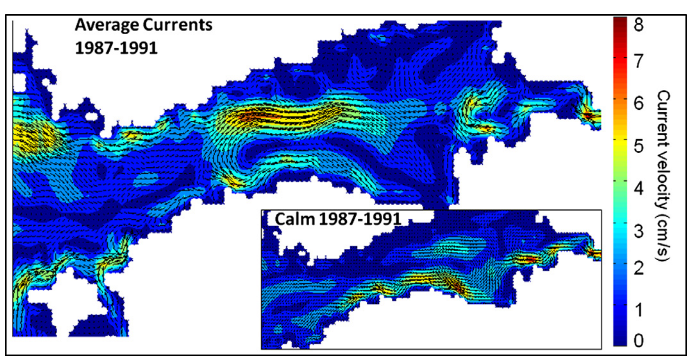

Fig. 20. Average velocity field, 1987–1991 (insert: during the May–August calm seasons over the same period), in the Gulf of Finland, calculated from simulations using the RCO model. Colour code shows current velocity in cm s^{-1} (from Soomere et al. (2011a)). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

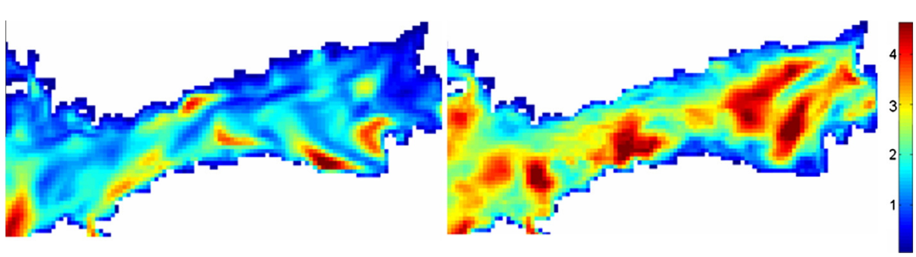

Fig. 21. The average *y*-component of the net transport velocity (cm s^{-1}) during the windy to calm season of 1987 (left) and the calm to windy season of 1988 (right) (from Soomere et al. (2011a)).

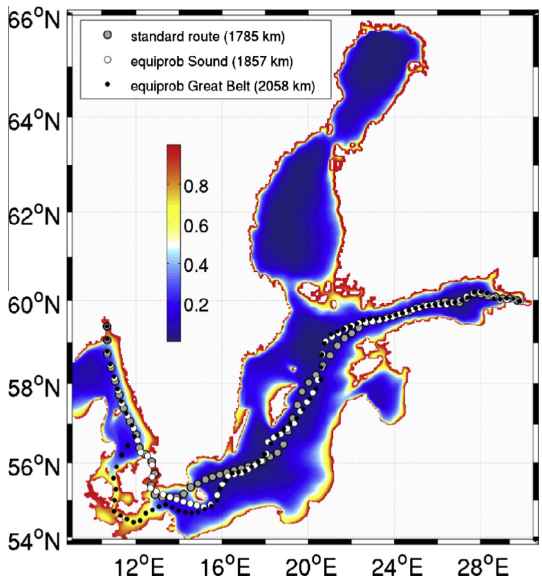

Fig. 22. Average probability of reaching the coast within 10 days from the instant of release calculated using the BSIOM model, 2002–2010 (colour scale). The grey dots indicate the frequently used shipping route from Oslo to Saint Petersburg. Environmentally safer fairways through the Sound and Great Belt are indicated by white and black dots, respectively (from Lehmann et al. (2014). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2011). The surface transport patterns exhibit strong seasonal variation (Murawski and Woge Nielsen, 2013). The overall flow regime has an even stronger impact on the Lagrangian surface transport patterns towards the coasts of the south-western Baltic Sea. Water parcels are relatively likely to drift towards the near shore during phases of surface water inflow from the North Sea into the Baltic Sea but are relatively unlikely to do so during outflow phases (Lu et al., 2012).

The basic properties of Lagrangian transport in subsurface layers of the Baltic Sea were studied for the first time in 2010–2011 using the Surface Velocity Program, with Barometer (SVP-B) drifters. Several triplets of such devices, each with a drogue at a depth of 12–18 m, were deployed in the Baltic Proper. The observed absolute dispersion (i.e., squared displacement from the initial position) and relative dispersion (i.e., spreading of initially closely located drifters in terms of their squared distance from each other) were considerably greater than similar values for virtual drifters advected using velocity fields from the two-mile RCO model (Kjelsson and Döös, 2012) and the TRACMASS code. The simulated currents were neither as fast nor as variable as those observed. Only some of these differences can be related to the moderate resolution of the ocean model used for comparison (Kjelsson and Döös, 2012). The model used probably tends to produce less mesoscale eddy activity than is observed. The spreading rates of shallow drifters (extending to a depth of 1–2 m) in the Gulf of Finland were variable, ranging from approximately 200 m day^{-1} for separations of <0.5 km to up to 0.5–3 km day^{-1} for separations of 1–4 km. The spreading rate does not follow Richardson's law (Richardson, 1926, for ocean studies see Lumpkin and Elipot, 2010) and has two considerably different regimes. The initial spreading, up to a distance of approximately d = 100–150 m, is governed by the power law, $d \sim t^{0.27}$, whereas for larger separations the distance increases as $d \sim t^{2.5}$ (Soomere et al., 2011c). These features call not only for increasing the formal resolution of existing Baltic Sea circulation models but also for improving their ability to replicate various dynamic features of water column processes.

Regional investigations have also been ongoing, particularly in the Gulf of Finland (Soomere et al., 2008, 2009). This basin has experienced a major increase in environmental risks due to strongly increasing traffic, particularly of oil tankers, and the construction of a gas pipeline from Russia to Germany. "Gulf of Finland Year 2014" has been organized by Finland, Estonia, and Russia to foster research and increase public awareness of the Baltic Sea.

Baltic Sea models and coupling to land and atmosphere

Introduction

A major modelling achievement of BALTEX Phase I was the building of high-resolution fully coupled atmosphere–sea-ice–ocean–land-surface models (Döscher et al., 2002; Gustafsson et al., 1998; Hagedorn et al., 2000; Schrum et al., 2003). The first coupled atmosphere–sea-ice–ocean model of the Baltic Sea region was developed to improve short-range weather forecasting using an accurate description of the lower boundary condition over sea (Gustafsson et al., 1998) and over land (Ljungemyr et al., 1996). The ice–ocean component included 2D, horizontally resolved ice and storm surge models and a 1D, vertically resolved ocean model applied to 31 Baltic Sea regions. Gustafsson et al. (1998) demonstrated that the model system together with data assimilation could successfully reproduce the convective snow bands over the Baltic Sea observed in January 1987.

To investigate and quantify the energy and water cycles in the Baltic Sea region, Hagedorn et al. (2000) developed a high-resolution fully coupled model based on a 3D ocean component; they demonstrated, for a three-month period in autumn 1995, that simulated SSTs are at least as good as, and in some cases even better than, the previously used SSTs obtained from operational analyses. However, Hagedorn et al. (2000) also demonstrated that the improved simulation of surface fluxes in the coupled model affects the atmospheric state variables only during periods when advective transports in the atmosphere are small.

At the end of BALTEX Phase I, the first coupled models that could reproduce even winter conditions including sea ice were available (Döscher et al., 2002; Schrum et al., 2003) and the first multi-year simulations were performed without artificial drifting (Döscher et al., 2002; Räisänen et al., 2004; Rummukainen et al., 2001). In addition to SSTs, ice concentration, heat fluxes, and other parameters were proven to be in good agreement with observations. For example, Lehmann et al. (2004) demonstrated that surface winds were well simulated and that the major Baltic inflow in January 2003 (e.g., Meier et al., 2004c) could realistically be reproduced using a coupled atmosphere–sea-ice–ocean model.

A prerequisite for multi-year simulations of the Baltic Sea is that the applied ocean models be able to simulate saltwater inflows through the Kattegat into the Baltic Proper, to continuously renew the Baltic deep water and keep the halocline stable. Whereas process-oriented Baltic Sea models had long since fulfilled these requirements (e.g., Gustafsson, 2000; Omstedt and Axell, 1998; Stigebrandt, 1983), multi-year simulations with high-resolution 3D ocean models that realistically reproduce saltwater inflow dynamics first became available at the end of BALTEX Phase I (e.g., Lehmann et al., 2002; Meier, 2001; Meier and Kauker, 2003a).

In addition, the realistic modelling of water and heat cycles requires high-quality atmospheric and hydrological forcing fields from models (Omstedt et al., 2000), observations (Omstedt et al., 2005), or reconstructions (Kauker and Meier, 2003; Meier and Kauker, 2003a). The generation and evaluation of such datasets for modelling purposes was another major achievement of BALTEX Phase I and an important prerequisite for the successful development of regional earth system models during Phase II. For further details, the reader is referred to Omstedt et al. (2004) and references therein.

Coupled atmosphere–ocean–land surface models

Whereas the first coupled atmosphere–sea-ice–ocean models were developed to improve short-range weather forecasting (e.g., Gustafsson et al., 1998) or to study the processes and impact of the coupling on air–sea exchange (e.g., Hagedorn et al., 2000), model development during the second phase of BALTEX focused more on studying climate change. Applying the so-called dynamic downscaling approach, regional climate models (RCMs) driven by global general circulation models (GCMs) at the lateral boundaries were used to assess the Baltic Sea in the future climate (e.g., Döscher and Meier, 2004; Meier et al., 2004a,b; Räisänen et al., 2004; Rummukainen et al., 2001). These earlier scenario simulations suffered from investigating only time slices that were brief compared with the Baltic Sea memory of approximately 30 years (e.g., Meier, 2002; Omstedt and Hansson, 2006a,b) and from considerable uncertainties in salinity projections (Meier et al., 2006a,b). Although transient simulations of the Baltic Sea over the 1960–2100 period have been performed in the meantime (e.g., Eilola et al., 2012, 2013; Friedland et al., 2012; Meier et al., 2011a, 2012a,b; Neumann, 2010; Neumann et al., 2012; Omstedt et al., 2012), projections of the future water balance remain fairly uncertain (Donnelly et al., 2014; Meier et al., 2012b).

In line with the extended objectives of BALTEX Phase II (i.e., studying climate variability, climate change, and biogeochemical cycles), increasing the complexity and/or resolution of the developed models was the main objective of model development. Coupled atmosphere–sea-ice–ocean models were further elaborated using a hierarchy of sub-models of the earth system combining RCMs with sub-models of surface waves (Almroth-Rosell et al., 2011; Rutgersson et al., 2012), land vegetation (Smith et al., 2011), hydrology and land biochemistry (Arheimer et al., 2012; Mörth et al., 2007), marine biogeochemistry (Daewel and Schrum, 2013; Eilola et al., 2009, 2011; Neumann et al., 2002; Savchuk et al., 2012), the marine carbon cycle (Edman and Omstedt, 2013; Gustafsson et al., 2014; Kuznetsov and Neumann, 2013; Omstedt et al., 2010), marine biology (Hense et al., 2013; Meier et al., 2011c), and food web modelling (MacKenzie et al., 2012; Niiranen et al., 2013) as well as with socioeconomic impact assessments (Piwowarczyk et al., 2012). Stimulated mostly by the BONUS + projects ECOSUPPORT (Meier and Andersson, 2012; Meier et al., 2014a), Baltic-C (Omstedt et al., 2014), INFLOW (Kotilainen et al., 2014), and AMBER (e.g., Dippner et al., 2010), these so-called regional climate system models (RCSMs) have been developed and applied to investigate the impact of climate change on the Baltic Sea ecosystem (Fig. 23). Hence, with the help of RCSMs, the combined impacts of multiple stressors (e.g., climate warming, eutrophication, and acidification) on the marine ecosystem could be studied (e.g., Meier et al., 2011a; Omstedt et al., 2012).

While at the beginning of BALTEX Phase II only two fully coupled atmosphere–sea-ice–ocean models were available (Döscher et al., 2002; Lehmann et al., 2004), today several research groups are developing coupled models of the Baltic Sea region (e.g., Dieterich et al., 2013; Gröger et al., submitted for publication; Hagemann et al., 2013; Pham et al., 2014; Tian et al., 2013).

To estimate uncertainties in future climate projections and past climate reconstructions, the multi-model ensemble approach has been introduced into earth system modelling of the Baltic Sea region following the well-established strategy of IPCC assessments (e.g., Meier et al., 2012c). Accordingly, the signal-to-noise ratio was calculated to estimate model biases, internal variability, and uncertainties due to unknown greenhouse gas emissions, nutrient loads, and fishery scenarios.

Notably, RCMs have been developed to study not only the future climate but also the past climate, including that of the past 100–1000 years (Gustafsson et al., 2012; Kabel et al., 2012; Hansson and Omstedt, 2008; Hansson et al., 2011; Meier and Kauker, 2003a,b; Meier et al., 2012c; Schimanke et al., 2012; cf. Section 'New datasets and tools').

Although the earth system approach has been greatly emphasized in modelling studies over the past decade, several modelling studies have also concentrated on improving our understanding of constituent processes of Baltic Sea dynamics that affect climate variability and change. Such processes include upwelling

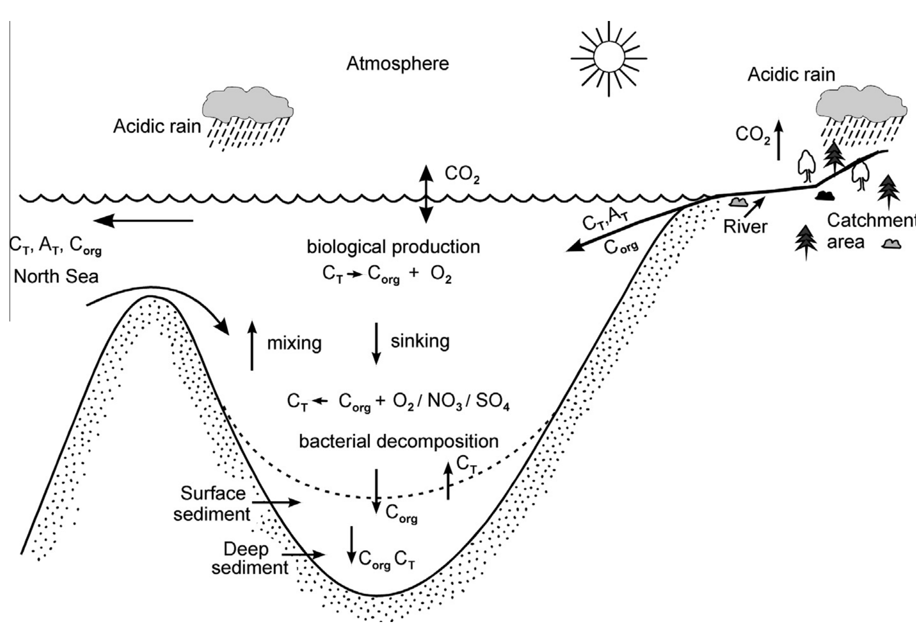

Fig. 23. Schematic of processes illustrating the land–atmosphere–ocean coupling of the Baltic Sea carbon cycle: C_{org} denotes organic carbon, C_T total inorganic carbon, A_T total alkalinity, and CO_2 carbon dioxide (including mineralization through oxygen/nitrate/sulphate ($O_2/NO_3/SO_4$) reduction (from Omstedt et al. (2014)).

(Myrberg and Andrejev, 2003), mesoscale dynamics (Zhurbas et al., 2004), overflow and dense water plume dynamics (Burchard et al., 2005), freshwater dynamics (Hordoir and Meier, 2010), regional circulation patterns (Andrejev et al., 2004a,b; Elken et al., 2011), thermal convection (Hordoir and Meier, 2012), halocline dynamics (Väli et al., 2014), water turbidity (Löptien and Meier, 2011), and deformed sea ice (Löptien et al., 2013).

These studies use 3D circulation models with high horizontal resolution. In the framework of the BONUS + project BalticWay (Soomere et al., 2014), the Gulf of Finland was simulated using a very high horizontal resolution of 0.25 nautical miles (Andrejev et al., 2010). Gräwe et al. (2013) studied saltwater inflows in the future climate using a model of the western Baltic Sea with a horizontal resolution of less than 1 km. In addition, the calculation of vertical transports in 3D ocean models has been improved by using non-uniform adaptive vertical grids (Hofmeister et al., 2010).

Modelling the land–sea continuum

As the Baltic Sea catchment area is four times larger than the Baltic Sea surface, the freshwater supply from rivers, which totals approximately 14,000 $m^3 s^{-1}$, is an important factor influencing the ocean dynamics in the Baltic Sea (e.g., Elken and Matthäus, 2008). Coupling hydrological and ocean models was therefore an important activity in BALTEX Phase II. In addition, the development of improved hydrological models for water management purposes was a specified objective, with an emphasis on more accurate forecasts of extreme events and long-term changes.

Earlier hydrological studies in BALTEX were often conducted by applying the large-scale HBV hydrological model (Lindström et al., 1997) to the entire Baltic catchment area (Graham, 1999, 2004). Recently, two new hydrological models have been developed to calculate future river flows and river-borne nutrient loadings, i.e., the Hydrological Predictions for the Environment (HYPE) model (Arheimer et al., 2012; Lindström et al., 2010) and the Catchment Simulation Model (CSIM) (Mörth et al., 2007). Despite these efforts, the uncertainties of runoff in scenario simulations for the end of the 21st century are considerable due to biases in precipitation calculated using regional atmosphere models (see Section 'Water and heat balances'). Projected nutrient loads are perhaps even more uncertain than are projected river flows due to unknown future land use and socioeconomic scenarios (Arheimer et al., 2012; Omstedt et al., 2012).

Modelling marine biogeochemical and carbon cycles

An important aspect of the policy-driven research in the BONUS + programme was the development of tools to support management, for example, focusing on the implementation of the Baltic Sea Action Plan (Backer et al., 2010). For this purpose, existing models of biogeochemical and carbon cycles have been further developed (e.g., Almroth-Rosell et al., 2011; Daewel and Schrum, 2013; Gustafsson et al., 2014; Omstedt et al., 2012; Savchuk et al., 2012). Eilola et al. (2011) compared three of these biogeochemical models for the 1970–2005 period and showed that all models reproduced the long-term oxygen-dependent dynamics of nutrient cycling in the Baltic Sea well. None of the models is significantly better or worse than the others and the ensemble mean is as good as or even better than the results of any of the individual models. However, all three models have problems in the northern Baltic Sea (Bothnian Sea and Bothnian Bay). Eilola et al. (2011) identified four major sources of uncertainties: (1) unknown initial conditions, (2) unknown bioavailability of nutrients in land runoff, (3) insufficient parameterization of sediment fluxes and the turnover of nutrients in sediments, and (4) the lack of process understanding for the Gulf of Bothnia. A more detailed review of studies of marine biogeochemical and carbon cycles is beyond the scope of this assessment.

Model synthesis

What have we learned from these new models? In particular, regional atmosphere models have enabled: (1) more detailed orography and improved spatial representation of precipitation; (2) improved land–sea masking; (3) improved sea surface boundary conditions (SST and sea ice) if a coupled atmosphere–sea-ice–ocean model is used; (4) more accurate modelling of extremes such as polar lows; and (5) more detailed representation of vegetation and soil characteristics (Feser et al., 2011 and references therein; Rummukainen, 2010). Over the sea, the value added by higher resolution is spatially limited to the coastal zone (Winterfeldt et al., 2010). In scenario simulations, the differences between uncoupled and coupled models might be considerable due to ice–albedo feedback (Meier et al., 2011b). Due to the long memory of the Baltic Sea (about three decades for salinity), transient simulations are needed. The impact of surface fluxes on summer SSTs is largest when the large-scale flow is weaker and more northerly than a stronger and more westerly flow over the North Atlantic (i.e., a high NAO index), causing larger differences between uncoupled and coupled simulations (Kjellström et al., 2005).

Hence, for consistent projections applying the dynamic downscaling approach to climate change, results of GCMs coupled with atmosphere–sea-ice–ocean models are needed. Other feedback mechanisms and their importance in perturbation experiments are currently under investigation. In particular, the water cycle modelling in RCMs still needs improvement.

Modelling circulation and water age

General questions

Three-dimensional circulation modelling is today an important tool for improving our understanding of the circulation dynamics of the seas and oceans. Recent Baltic Sea 3D models have been used, for example, to study the mean thermohaline and wind-driven circulations. As the Baltic Sea is an extremely demanding environment for numerical modelling, a few "hot spots" are briefly discussed before the main conclusions from the latest modelling work are summarized.

Today's 3D numerical modelling of the Baltic Sea is typically based on a horizontal resolution of 1–5 km and a vertical structure described by approximately 20–100 layers. In local applications (Andrejev et al., 2010; Lu et al., 2012; Zhurbas et al., 2008), even higher resolutions are often needed due to the low values of the baroclinic Rossby radius of deformation in the Baltic, i.e., only 3–10 km (see, e.g., Alenius et al., 2003; Fennel et al., 1991). Many of the dynamics of the Baltic Sea are apparently significantly affected by overall stratification, which determines the layered structure, and by local topography. A preliminary and approximate solution to this problem, recently implemented for the Gulf of Finland, for example, is to manually re-digitize information from navigational maps (Andrejev et al., 2010). This approach – obviously not proper 21st-century information technology – clearly reflects the problems faced by Baltic Sea oceanographers. High-resolution bottom topography information is urgently needed.

For relatively low-resolution simulations intended for model validation and inter-comparisons (Myrberg et al., 2010b) and for identifying long-term changes (e.g., Lehmann et al., 2011; Meier, 2006, 2007; Myrberg and Andrejev, 2006), properly adjusted geostrophic wind data (e.g., the gridded meteorological data provided by the Swedish Meteorological and Hydrological Institute) have been popular. As meteorological forcing, high-resolution Baltic Sea simulations typically use the output of local atmosphere models, such as different versions of the High Resolution Limited Area Model (HIRLAM) (www.hirlam.org) or the Deutscher Wetterdienst (DWD) model (www.dwd.de), or ERA-40 reanalysis data (Uppala et al., 2005) or their downscalings (Höglund et al., 2009; Samuelsson et al., 2011). As the resolution of such analyses is often too coarse for local hindcast studies and several systematic features of air flow in some basins are not captured (Keevallik and Soomere, 2010), new high-resolution reanalyses are urgently needed with about 1-km horizontal atmospheric model resolution. Despite recent developments, many questions remain to be answered; the challenges facing modelling in general are discussed at the end of this paper.

Mean circulation

The mean circulation of the entire Baltic Sea was modelled by Meier (2007), whose results agree with the main early findings of Palmén (1930) and the outcomes of other modelling studies (Lehmann and Hinrichsen, 2000; Lehmann et al., 2002) but also identify new fine-scale characteristics due to the higher resolution of the available models. The mean transports above and below the halocline agree with observational results and imply the existence of strong and possibly highly stable cyclonic gyres in both the Baltic Proper and Bothnian Sea (Meier, 2007). In the Eastern Gotland Basin, the model results reveal strong transports around the Gotland Deep, especially below the halocline, reproducing the observed deep rim current (Hagen and Feistel, 2007). Furthermore, modelling reveals that the strength and persistence of currents are lower in the Gulf of Riga, Gulf of Finland, and Bothnian Bay than in the Baltic Proper, possibly due to the impact of ice in winter or to the limited model resolution in the areas where the baroclinic Rossby radius is very small (Fig. 24).

The local wind field over the Baltic Sea can be related to large-scale atmospheric circulation via the Baltic Sea Index (BSI), which is the difference in normalized sea level pressures between Oslo in Norway and Szczecin in Poland (Lehmann et al., 2002). The BSI is related to the NAO index and, furthermore, highly correlated with the mean sea level of the Baltic Sea and the water exchange through the Baltic Sea. The mean circulation is likely variable over longer periods, with changes in the character of wind forcing, heat fluxes, ice extent, freshwater budget, and inflow activity. A hindcast for the 1958–2001 period indicates that yearly averaged surface velocities (i.e., mean over the whole sea area) have increased by 0.21 cm s^{-1} per decade (Jedrasik et al., 2008).

Deep-water circulation

Because the Baltic Sea is a permanently stratified system, a key physical feature is the deep-water circulation and its implications for the overall dynamics. There are still major gaps in our understanding of the physics of Baltic Sea deep-water dynamics. This subject was studied and reviewed by several earlier authors, but has been treated in only a few more recent studies (Elken and Matthäus, 2008; Matthäus, 2006; Meier et al., 2006a,b). The main problems are different inflows and stagnation periods, water exchange between basins, diapycnal mixing, eddies, and entrainment (Fig. 25).

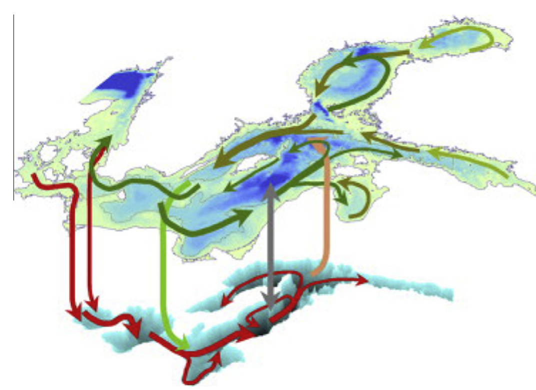

Fig. 25. Schematic of the large-scale internal water cycle in the Baltic Sea. The deep layer below the halocline is shown in the lower part of the figure. Green and red arrows show the surface and bottom layer circulations, respectively, the light green and beige arrows show entrainment, and the grey arrow shows diffusion (from Elken and Matthäus (2008)). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

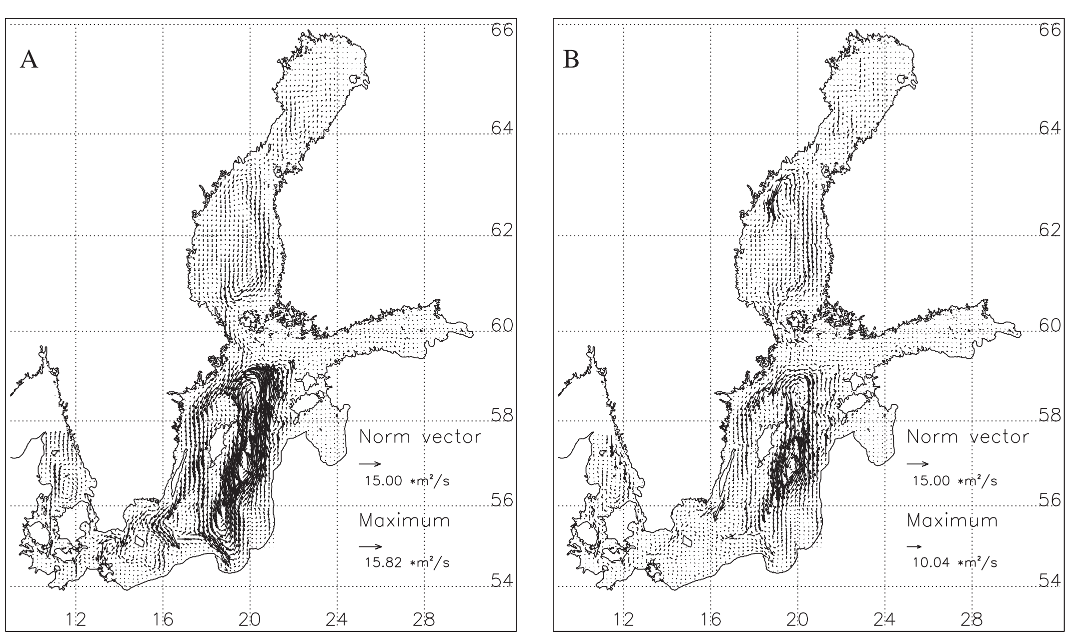

Fig. 24. Annual mean transport per unit length (m^2 s^{-1}), 1981–2004: (a) upper layer and (b) lower layer. Only every third grid point of the model is shown (from Meier (2007)).

Local modelling

The mean circulation in the Gulf of Finland has been modelled in local, detailed investigations by Andrejev et al. (2004a,b) and Elken et al. (2011). The cyclonic mean circulation in the Gulf of Finland is generally discernible but the resulting patterns and the high persistence of the currents deviate somewhat, according to Andrejev et al. (2004a), from those described in classical analyses by Witting (1912) and Palmén (1930). Both the mean and instantaneous circulation patterns in the Gulf of Finland contain numerous current loops whose size typically exceeds the internal Rossby radius. The results of a model study (1991–2000) by Myrberg and Andrejev (2006) support the traditional view of the cyclonic mean circulation in this basin. Its persistence is 20–60%, being greatest near the coasts, as indicated a long time ago by the observations of Witting (1912) and Palmén (1930). Especially in the Bothnian Sea, the persistence of the mean circulation approached that found by Lehmann and Hinrichsen (2000), who also used a barotropic model but covering a different period.

Water age

The main water age question is how long the water parcels inflowing into the Baltic Sea from various origins remain in the Sea? There are at least two approaches to solving the water age problem: Lagrangian and Eulerian approaches. Using 3D circulation model results, Döös et al. (2004) calculated the residence times of Baltic Sea water masses using Lagrangian particles released either at sills in the Baltic Sea entrance area or at the mouth of the River Neva, finding e-folding times of 26–29 years for both sites. These numbers are relatively close to the traditionally assumed water renewal time of approximately 30 years. One potential problem with the Lagrangian method is that sub-grid-scale mixing is not included, whereas Eulerian tracers do not have this problem.

The approach in which the sea water age is defined as the time elapsed since a water particle leaves the sea surface was used by Meier (2005). He found the mean age of bottom water to be one year in the Bornholm Deep, five years in the Gotland Deep, and up to seven years in the Landsort Deep. A slightly different approach is to assume that the age of the water inflowing from the source regions, i.e., river mouths and lateral open boundaries towards the Baltic Proper, is zero. Using this method, Andrejev et al. (2004b) and Myrberg and Andrejev (2006) found maximum water ages to be around two years in the Gulf of Finland and 7.4 years in the Gulf of Bothnia.

Other techniques can separate the ages of different water masses (Meier, 2007). These model simulations are based on the idea that passive tracers can mark, for example, inflowing waters within a certain temperature and salinity range or freshwater originating from rivers.

In the case of waters inflowing from the Kattegat, there are pronounced vertical and horizontal age gradients between the uppermost and near-bottom layers. The spatial distribution also indicates large differences in the water ages between the mouth area of the Baltic Sea and Bothnian Bay. At the sea surface, Belt Sea water is under 14 years old, whereas in the northernmost Baltic Sea the surface water is up to 40 years old. In the bottom layers, the water is generally younger than at the surface, for example, being under 10 years old in the Arkona Basin. The halocline separates the water masses of the upper and lower layers, which, in the Gotland Basin, are associated with ages under and over 26 years, respectively. The west–east cross-section of the Gotland Sea confirms that the surface water is older than the bottom water and that the Western Gotland Basin characteristically has older water than does the Eastern Gotland Basin due to its cyclonic circulation system.

The use of tracers to mark freshwater inflowing from all rivers indicates that the vertical age gradients in the Gotland Deep are much smaller than in the Kattegat, indicating the efficient recirculation of freshwater in the Baltic Sea. Such circulation is marked by downward tracer flux across the halocline caused by the entrainment of surface water into deep water, balanced by upward tracer flux caused by interplay between vertical advection and diffusion. According to Meier (2007), the greatest mean surface water ages, i.e., over 30 years, are found in the central Gotland Basin and the Belt Sea. Relatively young water is found only in the coastal zone and in river mouths. At the bottom, the mean ages are the greatest in the Western Gotland Deep at approximately 36 years. At the halocline depth, the age distribution is fairly homogeneous in the Baltic Proper – unlike the high spatial gradients indicated by age calculations based on inflowing waters.

Challenges for modelling

In 3D circulation models, sub-grid-scale processes are parameterized, which means that the impact of sub-grid-scale processes on the resolved motion is only considered using empirical relationships. Some of these parameterizations are typically used to calibrate these models using available observations, because many of the mechanisms are still unknown. We currently lack detailed knowledge of certain processes, i.e., bottom friction, vertical mixing, and surface fluxes of momentum, that are important for large-scale motions. The lack of knowledge of proper parameterizations of sub-grid-scale processes, insufficient horizontal and vertical grid resolution, biased atmospheric and hydrological forcing fields, overly coarse topographical datasets, and insufficient numerical schemes mean that Baltic Sea models suffer from uncertainties. Overcoming these shortcomings requires more observations, higher grid resolution, and improved parameterizations.

Tuomi (2014) has calculated the Stokes drift velocity, u_s, according to the theory proposed by Belcher et al. (2012) and the friction velocity, u_*, based on WAM model calculations in which 10-m wind from the Finnish Meteorological Institute's HIRLAM model was used. Accordingly, the Langmuir number, L_T, was derived as follows:

$$L_T = \sqrt{\frac{u_*}{u_S}}$$

This expression describes the relative influence of wind shear and Stokes drift on turbulence production. The calculations were carried out for the Gulf of Finland, 2002–2007, by Tuomi (2014). Several authors (e.g., Belcher et al., 2012) state that Langmuir circulation plays an important role in the vertical mixing when L_T is less than 0.7. According to Tuomi (2014), Langmuir circulation dominates turbulence production in the Gulf of Finland and its inclusion in the modelling of vertical mixing should be considered.

Some main findings

Baltic Sea research has made impressive progress over the past decade. For example, when BALTEX started in 1993, almost no scenarios were available; now many scenarios are available to the scientific community, many of them free of charge. The implication is that today's models can realistically reproduce many aspects of past and present climate and environmental conditions. Possible future changes have been modelled while taking account of uncertainties regarding both knowledge gaps and management options. BALTEX-generated knowledge is obviously crucial to society for managing our natural resources and further work is needed. The BALTEX programme, which started with basic science questions, and related programs during past decade have now yielded several achievements that are of great practical importance:

- Meteorological databases are available to the research community, partly as station data, including a growing number of freely available gridded datasets on decadal and centennial time scales. Though these freely available meteorological datasets strongly support the development of accurate forcing functions for Baltic Sea models, there is still a need for better temporal and spatial resolution. Gridded data entail several problems that need to be considered when calculating statistical properties such as trends and extremes, as various measuring techniques are used to acquire the data. The quality, accuracy, and resolution of the datasets therefore need further improvement.
- River runoff data are crucial for understanding several physical and environmental problems in the Baltic Sea (e.g., the mean salinity and stratification of the Baltic Sea closely follow variations in cumulative total river runoff), but it is still difficult to access such data. There is a great need to develop thoroughly tested hydrological databases including river runoff, nutrients, and carbon components for the entire Baltic Sea. This work needs to be strongly prioritized in future research.
- In the last decade, oceanographic data have become much more accessible and new important measurement platforms, such as FerryBoxes and satellites, have provided better temporally and spatially resolved observations. Few gridded oceanographic datasets are available, however. There is a need for better cooperation between the modelling and observation communities to develop data- and model-screening methods and data-assimilation products.
- Ice data are available from various data centres and data providers, though the data coverage is spatially and temporally irregular. Some model reconstructions are available but long-term ice data are difficult to access. As in sea ice research in general, ice thickness data are lacking and would be critical for model development and practical applications. New initiatives to generate freely available ice datasets are needed, together with assessments of data quality.
- We better understand how large-scale atmospheric circulation affects the Baltic Sea climate, particularly in winter. Internal variability is strong illustrating the stochastic behaviour in the atmosphere. Changes in large-scale atmospheric circulation in recent decades have caused a north-eastward shift in low-pressure tracks consistent with a more zonal circulation over the Baltic Sea basin. The reasons for these circulation changes are still debated and further research is needed.
- Our understanding of the heat and water cycles of the Baltic Sea has improved, and an increasing number of regional climate simulations are being performed. These modelling efforts still display severe biases with regard to temperature and precipitation under current climate conditions. Although eliminating these biases has been a key aim of BALTEX from the outset, heat- and water-cycle modelling still needs additional development.
- We have an improved understanding of the importance of surface waves in air–sea interaction. Stokes drift and Langmuir circulation seems to play an important role in surface water mixing. In addition, the role of stable atmospheric stratification (e.g., in upwelling regions) and ice–atmosphere heat flux parameterizations should be further studied.
- There has been progress in research into sea ice dynamics. Our understanding of the sea ice dynamics and thermodynamics in the coastal zone, where sea ice interaction with land and the central basin is key, has improved. However, more research remains to be done to measure and model the sea ice thickness.
- We now better appreciate the key role of the Baltic Sea's various straits and sills in water exchange and mixing. During intensive field campaigns it has been observed that the flow regimes are intermittent and that hydraulic control occurs less frequently than anticipated. In addition, in wider gravitational flows, transverse Ekman circulation has been observed that also influences mixing. The strait and sill areas are important and demanding environments that merit further research.
- There has been increasing interest in the coastal zone, particularly regarding upwelling, in the past decade of Baltic Sea research. The theory of upwelling is well understood, but new results indicate a need for more accurate atmospheric forcing and high-resolution Baltic Sea models that resolve meso-scale dynamics. This implies new research efforts to develop coupled sea–land–atmosphere models with high spatial and temporal resolution. The changing wind regime may alter the upwelling areas in the Baltic Sea, potentially affecting SSTs and ecosystem behaviour.
- Despite the highly transient current structure, several Lagrangian analyses of model results have provided evidence of the existence of highly ordered patterns of currents in the Baltic Sea, such as frequently repeating pathways of single particles as well as water masses or highly persistent flows. At the same time, observed drifters spread faster from each other than do virtual drifters advected using the modelled currents.
- Major improvements in the ocean modelling of the Baltic Sea–North Sea system have occurred, including the development of coupled land–sea–atmosphere models. Multi-decadal and centennial Baltic Sea model simulations based on process-based models and fully 3D models, including biogeochemistry components and with fairly high horizontal and vertical resolutions, are now available. A multi-model ensemble approach has been introduced into the Baltic Sea region for the first time. Major steps towards better understanding the physics and biogeochemical cycles of the Baltic Sea have been taken, ushering in a new decade of research oriented towards earth system modelling.

Outlook and future research needs

Despite the progress made in BALTEX and related research in the last two decades, several current gaps in our knowledge and understanding call for further inquiry. For example, although salinity is an elementary factor controlling the ecosystem of the brackish Baltic Sea, the current understanding of salinity changes is still very limited and future projections of the evolution of salinity are fairly uncertain. In addition, modelling of the hydrological cycle in atmospheric climate models is severely biased, and the bias corrections required in both the water and heat balances in these models indicate a great need for new research efforts. We still need more detailed investigations of regional precipitation and evaporation patterns (including runoff), atmospheric variability, highly saline water inflows, exchange between sub-basins, circulation, and especially vertical turbulent mixing processes. Such studies will require more sophisticated measurements, especially those made using remote-sensing techniques and direct measurements of turbulence. Furthermore, it is necessary to upgrade the resolution of the oceanographic models, which are mostly eddy-permitting but not eddy-resolving. There is also a great need to reanalyse meteorological model data to achieve high accuracy in the atmospheric forcing used in oceanographic circulation models. We also need new climate projections and simulations using improved atmospheric and oceanographic coupled model systems.

BALTEX has proven to be a productive science-driven programme free of significant influence from interest groups and with an outcome of considerable societal importance. The close links between universities and national institutions have improved the programme's work. After twenty years of intensive research and outreach activities, BALTEX ended in 2013. As scientists regarded BALTEX as a very successful research programme, the science steering group agreed to launch a successor programme under the new name "Baltic Earth", with a revised focus on earth system science and led by a steering group committed to continuing interdisciplinary and international research collaboration in the Baltic Sea region. Although Baltic Earth will face new challenges, it inherits the BALTEX network of scientists and institutions, its infrastructure comprising the secretariat, study conferences, workshops, and publications, and its scientific legacy. Like BALTEX, the new programme aims to be embedded in international, global-scale programmes such as GEWEX/WCRP and Future Earth.

The vision of Baltic Earth is to achieve an improved earth system understanding of the Baltic Sea region (Meier et al., 2014b). Specific "Grand Research Challenges" have been formulated that will represent interdisciplinary research questions to be addressed by the new programme in the coming years. Service to society will be provided in that thematic assessments of particular research topics, compiled by expert groups, will help to identify gaps in current knowledge that need to be filled (e.g., by funded projects). An example of such a thematic assessment is the BALTEX Assessment of Climate Change for the Baltic Sea Basin (BACC), which summarizes current knowledge of past, present, and future climates in the Baltic Sea region, following the approach of the Intergovernmental Panel on Climate Change, but with a much more pronounced regional focus. One important activity of Baltic Earth will be to continue this series of assessments. The following Baltic Earth Grand Research Challenges have so far been identified:

- Salinity dynamics in the Baltic Sea.
- Land–sea biogeochemical feedbacks in the Baltic Sea region.
- Natural hazards and extreme events in the Baltic Sea region.
- Understanding sea level dynamics in the Baltic Sea.
- Understanding regional variability of water and energy exchange.

Within these Grand Research Challenges, anthropogenic changes and impacts will be treated together with their natural drivers. In addition to the scientific challenges, outreach and education are expected to be strong components of Baltic Earth. With our new tools in terms of instruments, ships, satellites, reanalysis data products, and freely available data and models, good research progress can be expected.

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